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Ground-based high energy power beaming in support of spacecraft power requirements

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

GROUND-BASED HIGH ENERGY POWER BEAMING IN SUPPORT OF SPACECRAFT POWER REQUIREMENTS

by

Christopher M. Guoan

June 2006

Thesis Advisor:	Sherif Michael
Second Reader:	Don Wadsworth

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This thesis investigates the feasibility of projecting ground-based laser power to energize a spacecraft electrical bus via the solar panels. The energy is projected through a telescope, using modern optical compensation systems, at controlled wavelengths. Research conducted on high-energy lasers has matured to the point today, that the bulk of the power required by spacecraft on orbit can be projected from the surface of the earth. With battery life being the greatest limitation on spacecraft lifespan, the ability to provide electrical power from the surface to a satellite in eclipse with degraded batteries could mean multi-billion dollar cost savings by extending the lifetime of current and future satellites.

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GROUND-BASED HIGH ENERGY POWER BEAMING IN SUPPORT OF SPACECRAFT POWER REQUIREMENTS.

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requirements for the degree of

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ABSTRACT

This thesis investigates the feasibility of projecting ground-based laser power to energize a spacecraft electrical bus via the solar panels. The energy is projected through a telescope, using modern optical compensation systems, at controlled wavelengths. Research conducted on high-energy lasers has matured to the point today, that the bulk of the power required by spacecraft on orbit can be projected from the surface of the earth. With battery life being the greatest limitation on spacecraft lifespan, the ability to provide electrical power from the surface to a satellite in eclipse with degraded batteries could mean multi-billion dollar cost savings by extending the lifetime of current and future satellites.

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First, I would like to thank my thesis advisors, Professor Sherif Michael and Professor Don Wadsworth, for their guidance and mentorship during the long process producing this thesis research. Additionally, I would like to thank Richard C. Luce, Jr. for the initial study of this topic area. Without his work, this project may have never gotten off the ground. Finally, I would like to thank my wife Amy and my son Tad for their support and understanding that was vital in allowing me to put in the long hours of research and spend the financial resources necessary to complete this project.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ADONIS	Adaptive Optics Near Infrared System
ADOPT	Adaptive Optics module of Telescopio Nazionale Galileo
ALFA	Arecibo L-band Feed Array
AMOS	Air Force Maui Optical Station
ANSI	American National Standards Institute
AO	Adaptive Optics
AOS	Active Optics System
APD	Avalanche Photo Diode
ARC	Australian Research Council
ATM	Asynchronous Transfer Mode
AURA:	Association of Universities for Research in Astronomy
BOL	Beginning of Life
CARA:	California Association for Research in Astronomy
CFHT	Canada-France-Hawaii Telescope
CGG	Centro Galileo Galilei
ChAOS	Chicago Adaptive Optics System
CNAA	Consorzio Nazionale per l'Astronomia e l'Astrofisica
COP	Common Operational Picture
CoS	Class of Service
DARPA	Defense Advanced Research Projects Agency
dBm	Decibels referenced to 1 mW
DoD	Department of Defense
EOL	End of Life
ESA	European Space Agency
ESO	European Southern Observatory
FDHM	Full Duration at Half Maximum
FWHM:	Full Width at Half Maximum
Gbps	Gigabits per second
GEO	Geosynchronous Earth Orbit

GUI	Graphical User Interface
HEO	Highly Elliptical Earth Orbit
HO	Higher orders
IfA:	University of Hawaii's Institute for Astronomy
INAF	Italian National Institute of Astrophysics
ISB	Instrument Support Box
IRCAL	AO-optimized IR camera
ITU	International Telecommunications Union
kbps	Kilobits Per Second
km	Kilometers
LEO	Low Earth Orbit
LGS	Laser Guided Star Projector
LLNL	Lawrence Livermore National Laboratories
Mbps	Megabits per second
MCAO	Multi-Conjugate Adaptive Optics
MEMS	Microelectromechanical Systems
ms	Milliseconds
mW	Miliwatts
NAIC	National Astronomy and Ionosphere Center
NAOS	Nasmyth Adaptive Optics System
NGS	Natural Guide Star
NICMOS	Near Infrared Camera Metal Oxide Semi-conductor
nm	Nanometers
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NSF	National Science Foundation
NTT	New Technology Telescope
ORM	Roque de Los Muchachos Observatory
PICNIC	Planetary Integrated Camera Near-Infra-red Camera
PoC	Proof-of-Concept
PPARC	UK Particle Physics and Astronomy Research Council

QoS	Quality of Service
SAAO	South African Astronomical Observatory
SDIO	Strategic Defense Initiative Organization
SINFONI	Spectrograph for Integral Field Observations in the Near Infrared
SOAR	Southern Observatory for Astrophysical Research
SOR	Star-fire Optical Range
SWIR	Short Wave Infra Red
ToS	Type of Service
TNG	Telescopio Nazionale Galileo
T/T	Tip/Tilt
VLT	Very Large Telescope
WFS	Wave Front Sensor

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NOMENCLATURE

Alt = Altitude, km

AM0 = 1366.1 W/m^2, (Perihelion: 1412.5 W/m^2, Aphelion: 1321.7 W/m^2)[1]

c = speed of light, $2.998 \cdot 10^8$ m/sec

d = source to receiver distance, m

h = Plank's Constant, 6.626069 x 10^{-34} J·s (4.13567 μeV/ GHz)

h = orbital altitude above the Earth's surface, in units of Earth radii

I_{sp} = specific impulse, seconds

r_e = Radius of the Earth, km

r_{lens} = radius of lens or mirror used as beam director, m

r_{spot} = radius of laser beam at receiver, m

v = orbital velocity

VF = fraction of time that orbit is in view of ground station at given zenith angle

α = laser pointing angle measured from zenith, radians

Δ = point-ahead distance, m

ΔV = velocity change, m/sec

λ = laser wavelength

1 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00, Solar Spectra: "Standard Air Mass Zero," <http://rredc.nrel.gov/solar/spectra/am0/ASTM2000.html>, (May 2006).

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EXECUTIVE SUMMARY

Modern technology has advanced to the point today that Geoffrey Landis's 1989 proposal to beam power from the ground to space in support of orbiting satellites can become a reality. The need for further development in this arena is ripe as burgeoning technologies like high-power solid state lasers have reached the point at which they can provide the power requirements needed to fully energize a satellite even during eclipse.

In general, hundreds of satellites in Geostationary orbit (GEO) are reaching end of life due to nothing more than the exhaustion of their battery life. With the average transponder creating over $1.5 million in annual revenues in 2002[2], and with each satellite having a average number of 40.5 transponders[3] in 2003, the annual benefit of keeping one satellite operational beyond its battery life is easily in excess of $60 million per satellite. A modern communications satellite costs on average half a billion dollars to build without counting launch costs, which, for today's large communications satellites, runs well into the quarter billion dollar bracket (about $5000/pound). The cost savings of not having to build and launch just one new satellite would be over a quarter of a billion dollars. With around 29 GEO satellites being launched every year (26 commercial and 6 military in 2004[4]), the cost of putting those satellites in orbit conservatively costs over $7.5 billion.

The construction of seven telescope facilities with the capability of 24 hour a day, 365 days a year, coverage of satellites at GEO at an individual extravagant cost of $200 million per facility, double the expected cost, would only be $1.4 billion. This is in line with the cost of replacing just one satellite and actually probably double the real price tag.

The fundamental concept of power beaming is the use of terrestrial power sources to send power into space as a coherent directed beam of photonic energy with useful power levels similar to that of the sun. With the sun producing 1353 W/m^2 and solar panel efficiencies at 18%, the sun provides 244 W/m^2 to the spacecraft. Current solar cell

2 Loral Space & Communications, "Loral Reports Results For Periods Ended September 30, 2002," 7 November 2002, <http://www.ssloral.com/html/pressreleases/021107.html>, (May 2006).

3 Futron Inc, "Space and Telecommunications: Satellite Services," May 2006, <http://www.futron.com>, (May 2006).

4 Futron Inc, "Space and Telecommunications: Satellite Services," May 2006, <http://www.futron.com>, (May 2006).

efficiencies that average about 18% on the high end can be boosted by around 45 to 50% using coherent (nearly monochromatic) laser power. This means a beam of energy from the earth need only provide 900 W/m^2. As more of the arriving energy is converted to space bus power and less goes into the production of heat, more solar cell output voltage is available. Reduced heat loading, due to greater efficiency, means output voltage increases by two milivolts per typical cell per degree Kelvin temperature decrease. This decrease in temperature also there for has the effect of increasing efficiency.

A primary motivation for laser powering is to restore geosynchronous satellites to useful service during eclipse (which can last up to 70 minutes) despite exhausted batteries. There are many other reasons for this capability addressed in the chapter on power beaming. A few of the more important side benefits are to supply surplus power to satellites on orbit for purposes of attitude adjustment, orbital maneuvering, and station keeping for spacecraft equipt with electric propulsion engines. Another desirable capability is solar panel annealing to repair the annual degradation caused by the impact of cosmic particles on the solar array. There are many other benefits, but these are the major points.

Unfortunately, there is a cost associated with the research and development of the technologies required to provide this type of capability. International agreements must be formulated as no one country spans the globe or controls the GEO orbit. Most satellites are built by private companies and not by governments. A convincing argument would have to be made and presented to these companies to enlist their help in covering the cost of preconstruction of the proposed power beaming facilities. Sites will have to be located that provide the most optimal conditions of air clarity and good weather. Finally, the people that control the money and political will of the people must be educated that the capability even exists.

The purpose of this paper is to consolidate the information required, and to educate the public in the concepts of directed energy and power beaming. Myths of aircraft and spacecraft flying through these laser beams and being destroyed will be dispelled by this argument. This thesis will show the power contained in the beam will have little more effect than spending a hot day at the beach on anything that was to pass

into the beam. Further more, the beam will be invisible to the naked eye as it is propagated at a frequency outside of the visible range.

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I. INTRODUCTION

A. MOTIVATION

A long personal interest in all-things-space and the opportunity to achieve a masters degree in Electrical Engineering led me to the classes of Dr. Sherif Michaels where a chance to work in an interesting topic and the lure of a possible paid trip to Hawaii was overwhelming. Several other offers became less appealing, though better funded, and a final decision to pursue a thesis on power beaming as a means to provide spacecraft power to on-orbit satellites became the joint decision of my family and myself. I am sure the family was a little more motivate on the possibility of a trip to Hawaii, but either way, it was the right decision.

B. THESIS OBJECTIVE

The goal of this thesis is to educate the reader on the very real and cost effective possibility of providing orbital packages power, either incident or in excess of onboard capabilities, for the purpose of weight savings, life extension, attitude adjustment, station keeping, or orbital maneuvering. The possibilities of other applications of this technology will also be discussed.

C. RELATED WORK

The work in this thesis comes as a direct result of the interests of Professor Sherif Michaels in conducting further research in solar cell powering from ground based sources and because of the work produced by Richard C. Luce, Jr. in his thesis titled, “Spacecraft Power Beaming And Solar Cell Annealing Using High-Energy Lasers.” His look at providing ground-based power for space-based applications opened the door to a more in-depth look at the possibilities of this technology.

The earliest source reported on power beaming was by Peter Glaser. In 1968, he first suggested beaming power from space to the ground. Edward J. Conway and R.J. De Young conducted the first work for the purposes of powering spacecraft in their essay titled, "Beamed Laser Power for Advanced Space Missions," in 1989. Some initial work was conducted by Geoffrey A. Landis, also in 1989, and presented at the 40th

International Astronautics Federation Congress, Dresden, GDR, in October 1990. Landis was the first to suggest beaming power from the earth to space. The follow-up work in this area was concluded and presented publicly by Geoffrey A. Landis, Mark Stavnes, and Steve Oleson from Sverdrup Technology, Inc., NASA Glenn Research Center along with John Bozek of the NASA Glenn Research Center when they highlighted their finding and produced a paper for the 43rd IAF Congress, 28 Aug.-5 Sept. 1992, in Washington DC. Their initial investigations into the subject then coined the phase, "Power Beaming."

D. THESIS ORGANIZATION

The thesis is organized in *chapters*, with *sections* within the chapters, and *subsections* within the sections. All minor references are footnoted at the bottom of the page on which it is used. Additionally, major references are collated alphabetically by the lead author's last name in the reference appendix.

Chapter II covers what power beaming is and why is it important to us. Chapter III introduces information on electromagnetic (EM) radiation and points to our use of the spectrum for the purposes of energy transmission. It talks about lasers, and the various types. The chapter then summarizes the military High Energy Lasers (HEL) in testing that may be applicable for our current use or for future development. Chapter IV takes a look at the science of optics and how it relates to power beaming. Chapter V evaluates the application of optics for use in power beaming, namely the use of telescopes greater than 3.5 meters with adaptive optical packages. Chapter VI looks at solar cells, what they are made of and how they work. Chapter VII looks at the Naval Postgraduate School next satellite and our possible experimental application with it. Chapter VIII provides an overall summary of our topic to include a series of conclusions and suggestions for future research. The argument follows with several appendixes that look at various elements of the science, technology and systems that the advanced reader might be interested in finding out more about. A glossary is included to help give a definition to many of the terms the author has used or otherwise defined.

E. THE AUDIENCE

This thesis is written to the scientifically interested, not necessarily the scientifically educated. A person with a basic science background should be able to follow the argument without becoming overwhelmed by the details of the science. In addition, the audience is not supposed to have advanced knowledge in any area relating to power beaming. The argument canvases the theory and the application from the science of power generation through transport and application. Finally, the argument suggests alternate applications and possible follow-on research possibilities including the possibility of a near-term experiment.

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II. POWER BEAMING

A. CHAPTER OVERVIEW

This chapter discusses what power beaming is and why is it important to us. Power beaming is the transmission of energy through a non-solid medium. Wikipedia[5] says, “Beaming enough energy to run a machine (such as a vehicle) is called power beaming.” It is important to us as a cost savings measure and is the emphasis of this argument.

While the use of lasers to transmit power to photovoltaic arrays was proposed by Backus in 1972, applications suggesting the use of ground-based power beaming to power satellite have only been proposed since 1989. Today, technological advances in high-power lasers and adaptive optics have made such concepts more realistic.

B. AN EXPLORATION INTO POWER BEAMING

There are two inherent reasons for investment related to space. The use of space is sometimes the cheapest way of doing a thing. Sometimes it is the only way of doing that thing. Investment in space hardware is exclusionary in nature. The costs associated with development of space hardware are prohibitive. Investors in space are normally sponsored by nation states. For the relatively few nations that participate in a space program, the very expensive launch vehicles and spacecraft are relatively short lived.

Research conducted on high-energy lasers has matured to the point today, that the bulk of the power required by spacecraft on orbit can be projected from the surface of the earth. With battery life being the greatest limitation on spacecraft lifespan, the ability to provide electrical power from the surface to orbit to a satellite in eclipse with degraded batteries will mean multi-billion dollar cost savings to current and future programs in the ability to continue to fly current and future payloads longer.

The motion of energy is the key to our discourse. There are three known way to move energy: by *storage* in a battery, capacitor, chemical state, an electromagnetic field or mechanical state, *plumbed* through a medium such as a wire, fiber optic cable, or

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5 Wikipedia, Category: Energy development, “Power Beaming,” 3 December 2005, <http://en.wikipedia.org/wiki/power_beaming>, (Last Referenced: Jan 2006).

waveguide, and *beaming* through a permeable material such as a fluid, gas, or free space as an electromagnetic wave (EM). Beaming of EM radiation is the mode of importance to our discussion. An understanding of what EM radiation is a topic of enough importance to power beaming to dedicate a chapter to it and its effects.

Our objective in discussing power beaming is to provide energy to a remote machine, in this case to provide power in a form that a satellite can use. This is not the only use for power beaming; there are other applications such as communication, heating, welding, and lasing of materials, but for the purposes of our discussion, we will consider the basic propagation of energy from the ground to a vehicle on orbit. The STARFIRE Optical range in the New Mexico desert is shown propagating a ground-based laser into space, Figure 1

Figure 1 STARFIRE Optical Range, NM

1. Power in Eclipse

There are many uses for power beaming technology. The first and most obvious use would be to power orbital vehicles in eclipse as depicted in Figure 3As the satellite enters eclipse, a laser array fed through a ground-based telescope would illuminate the solar arrays on the satellite to a level sufficient to provide operating power. Use of seven

isolated locations will result in over 99.9% beam availability.[6] This may be important in extending the life of a satellite as batteries have a relatively short life and become the life-limiting factor of the satellite that they power. Once the batteries have degraded to a point, the satellite may become nothing more than space debris. With terrestrial power beaming, vehicles in eclipse could receive the energy they need reducing or eliminating the need for on-board batteries all together.

The spacecraft in eclipse must rely on the onboard batteries to supply the minimum power required by the spacecraft. Battery performance also suffers over time with cyclic charging and discharging. Satellites at Low Earth Orbit (LEO), from 240 km to 1000 km, have an orbital period of around 90 minutes. The 90 minutes actually corresponds to and altitude of 540 km, though it does not change too much at these altitudes. Batteries for these satellites must carry a minimum load for between 38 minutes, for 240km orbit, to 30 minutes, for 1000km orbit LEO satellites, out of every roughly 90 minute orbit, depicted in Figure 2

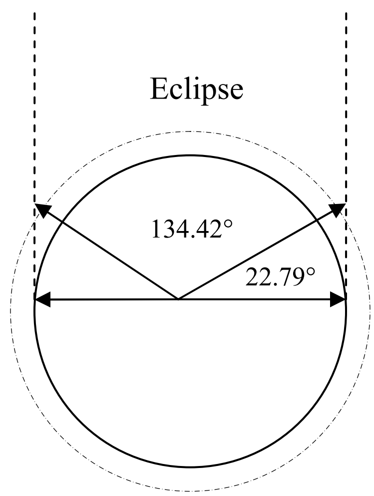

Figure 2 Time of LEO Eclipse

[6] N. Bloembergen *et al.*, "Beam Control and Delivery," Chapter 5, *Science and Technology of Directed Energy Weapons, Report of the American Physical Society Study Group,* pp. 175-240, (April 1987)

$$Altitude_{240} = 6378km + 240km = 6618km \tag{2.1}$$

$$ArcCos(6378/6618) = 15.48° \tag{2.2}$$

$$Altitude_{540} = 6378km + 540km = 6918km \tag{2.3}$$

$$ArcCos(6378/6918) = 22.79° \tag{2.4}$$

$$Altitude_{1000} = 6378km + 1000km = 7378km \tag{2.5}$$

$$ArcCos(6378/7378) = 30.18° \tag{2.6}$$

Equations 2.1, 2.3 and 2.5 are the orbital altitude equations corresponding to altitudes of 240 km, 540 km, and 1000 km respectively. Equations 2.2, 2.4, and 2.6 are calculations for the above quoted times in eclipse ($t_{eclipse}$).

$$t_{eclipse} \simeq 90\text{minutes} \times (134.424/360) = 33.6\text{minutes} \tag{2.7}$$

A roughly 90-minute orbit equates to sixteen orbits and sixteen cycles on the battery every day. This tremendous strain means that battery life will be short lived, typically three to five years depending on type and cycle loading.

A power beaming system based on a continuous wave laser, telescope, and adaptive optics system able to provide enough power from the ground would extend the life of this type of satellite for a much greater period. Batteries that normally account for 48% of the power system mass of a satellite, could be reserved, reduced, or eliminate from future designs based on a proven ground based power transmission system. Theoretically, the solar cell degradation would then compete with orbital decay for determination of end of life for these power beam supported satellites. For satellites at higher LEO, degradation of the solar array is more likely to win the contest.

A Geostationary (GEO) satellite, with an orbital altitude of 42,164 km, spends a maximum of less than 70 minutes per day in eclipse (refer to equations 2.1 through 2.6). This time is actually slightly less due to diffraction of light by the earth's atmosphere providing a reduced amount of light for a transition period after geographic eclipse. The satellites, by orbit of inclination as referenced to the plane of the ecliptic, reaches this maximum only twice a year for a period of about 45 days. The depth of battery depression experience mitigates the reduced number of cycles during annual cumulative eclipse. Typical battery life on GEO satellites are from ten years to fifteen.

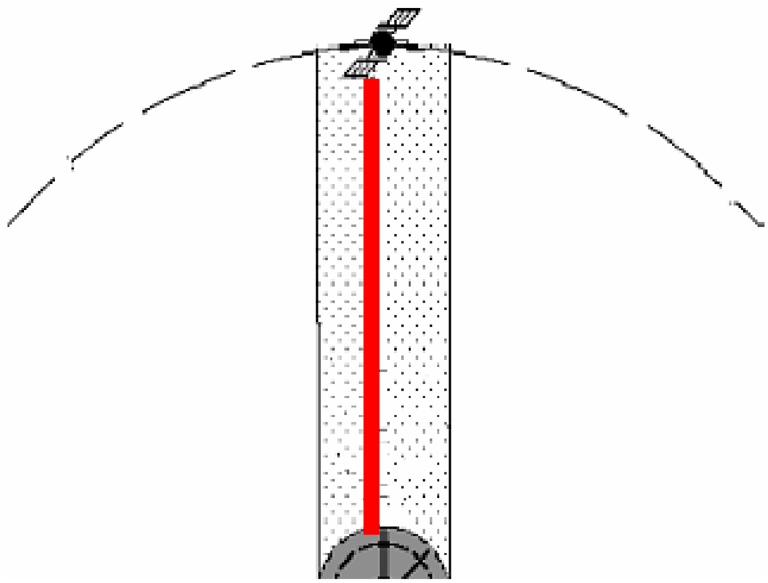

Figure 3 Diagram of a Satellite in Eclipse of the Earth's shadow

The typical "bent-pipe" or repeater technology of the communications GEO satellites has not changed significantly except in the power available and the increased number of transponders. The predominant mission of the communications satellites is as repeaters, though more are beginning to be flown with an on-board processing capability (OBP). Repeaters receive a signal, amplify it, and rebroadcast it.

Fixing the number of satellites at GEO is hard. With this real estate being the most value on or around the planet, international law in various forms has attempted to govern its allocation. The real estate itself has been divided into 2° increments by the ITU, which would suggest that there could only be 180 satellites at this valuable orbit, but that is far from the case. According to the Federal Aviation Administration's Office of the Associate Administrator for commercial Space Transportation, the first satellite launched to GEO was Syncom 1 in 1963. Since then there have been more than 500 launches to GEO as reported in 1995. Now, eleven years later, estimating 27 launches annually to GEO based on reported commercial and military, the number of spacecraft is believed to be more in the neighborhood of 810. Of these, 587-597 are still thought to be operational, based on 2001 numbers.[7]

[7] Marco Caceres, "Oribiting Satellites: Gean-counter's heaven," *Aerospace America* (August 2001)

In 1991, there were 168 operating non-military satellites in the K and C bands at GEO along with 22 non-operational satellites. Using these statistics alone and not looking at the other types of satellites at GEO, Dr. Landis made the argument that, with an average lift of 20 to 25 satellites a year over the past fifteen years to GEO at an average cost of between $136 million and $250 million production costs alone, the number of candidate satellites would be about 350 not including military payloads. In addition, there would be another roughly 170 dead or dying platforms in eternal orbit that may be able to reap some benefits from power beaming. With the typical transponder creating revenues of $1 million per year after assuming a 50% discount for age and degradation, and further assuming a base of 8 transponders per satellite (figure based on the minimum number of transponders on a late 1980's satellite, typical being 24), a ground based system which could significantly extend the life of orbiting GEO satellites alone, could theoretically provide a cost benefit very conservatively of well into $2 billion per year.[8] This figure is based on 1991 projections. If even half of the estimate 597 satellites at GEO today could be counted as possible candidates, the figure would be even greater. If the service life of these satellites was extended by power beaming to provide power in eclipse negating the need for batteries, the continued revenue without cost of replacement would easily eclipse the cost of building and operating an entire array of ground based emitter stations. For those satellites that are not revenue generating, the cost of replacement is even more critical, making even a stronger argument that a ground based array of seven global transmission sites should be considered.

2. Power Augmentation

Similar to providing power in eclipse would be providing power to GEO vehicles that are nearing end of life and suffering the affects of solar cell degradation. An application of ground-based power beaming would be to provide these systems with the ability to produce more power by providing the solar array with a greater number of photons at a greater concentration slightly higher than that provided by our sun. This

[8] Geoffrey A. Landis, "Laser Beamed Power: Satellite Demonstration Applications," Paper Iaf-92-0600, 43rd Iaf Congress, 28 Aug.-5 Sept. 1992, Washington DC.

effect will provide aging systems with some badly needed relief. It can also be used to provide power for end of life disposal by orbit rising or lowering depending on the mode selected.

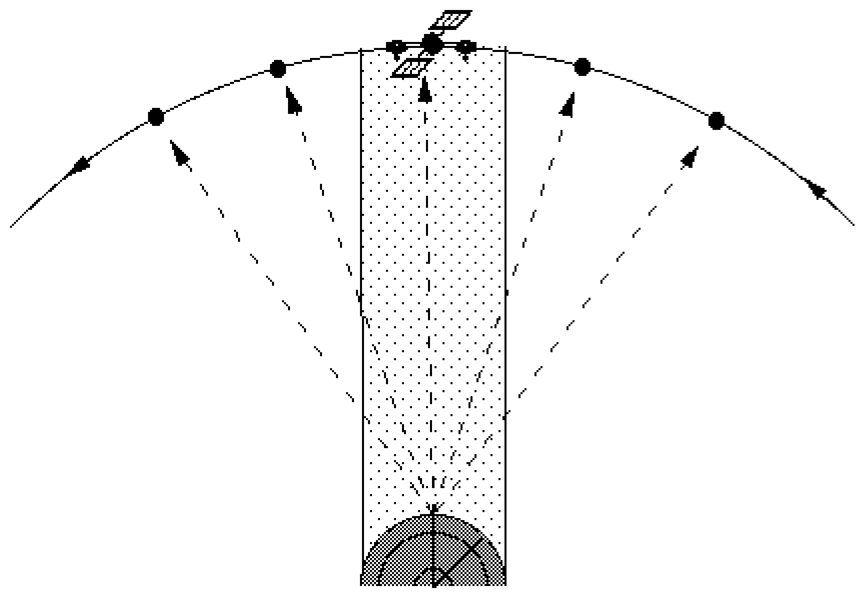

Figure 4 Ground Based Power Beam Angular Capability[9]

3. On-orbit uses for Beamed Power

Once power is beamed to a satellite solar array aboard an orbital vehicle, energy can be used to power the various onboard payloads such as vehicle electrical systems, computers, attitude control systems, orbital maintenance systems and orbital transfer systems. Some applications require higher power for a short amount of time such as station keeping. Power beaming has the capability of providing this higher average power because of the control of the coherence of light emitted by the ground based power emitter and the similar control of peak power levels. Efficiency of power transfer may easily be about 50% as the solar cell experiences less heating effects as the power beamed is in exactly the wavelength the solar cell requires. This ability to focus conditioned power will be discussed later in chapter0. The ability to provide constant ground based power can also be used to compensate for solar flux on the solar arrays as required. The major requirement to take advantage of this technology would be the

9 Geoffrey Landis, "Satellite Eclipse Power By Laser Illumination," 8 July 2002, <http://powerweb.grc.nasa.gov/pvsee/publications/lasers/IAF90_053.html>, (Apr 2006).

necessary redesign of future systems to handle the increased power generated. Current systems could benefit as well, but a system designed to operate for short amounts of time with increased power for such applications as orbital maneuvers would be one significant application of this unique source of power.

> On a typical communications satellite, about 1/5 of the total satellite mass is the power system. For a 5kW power system, the power system total mass is roughly 900 kg. The energy storage system, for current nickel-hydrogen batteries used in GEO, comprises 42% of the power system weight. An additional 37% of the power system mass is electrical power conditioning, a significant portion of which is needed for battery charge regulation. Only 21% of the power system mass is actually the solar array, and about 10% of the array area is dedicated to recharging the batteries. It is remarkable that over half of the mass of the power system has no other function than to provide power for less than one percent of the operating time. Eliminating the requirement for an energy storage system could reduce satellite mass by 10%.[10]

4. Propulsion

Providing ground-based power for propulsion on orbit will save weight and reduce orbital maneuvering times. In applications such as raising and lowering orbit, these times can be reduced to a small percentage of that require when powered by the sun alone. Modern satellites use electric and ion engines for maneuvering, station keeping, and orbit transfer. The benefits of these systems are that they are more efficient requiring less on-board payload to do the same work as the cold gas and bi-propellant systems.

While electric propulsion lacks the brute thrust of bi-propellant reaction engines, it is entirely more efficient. The typical chemical rocket has a Specific Impulse ($I_{SP)}$ of around 300 seconds. This is typical of the engines that are required to raise payloads off the surface of the earth with Single Stage to Orbit propulsion systems. The high I_{SP} engines have significantly less thrust and are incapable of attaining orbital velocities in the earths atmosphere, but once placed on orbit with I_{SP}'s of 3800 seconds and thrust levels of 165 N·m,[11] are quite capable of delivering propulsion capable of raising orbit, station keeping or providing multi-axis stability. The use of ion engines significantly

[10] Geoffrey Landis, "Satellite Eclipse Power By Laser Illumination," 8 July 2002, <http://powerweb.grc.nasa.gov/pvsee/publications/lasers/IAF90_053.html>, (Apr 2006).

[11] Boeing, Public Relations, "Xenon Ion Propulsion," <http://www.boeing.com/defense-space/space/bss/factsheets/xips/xips.html>, (Apr 2006).

reduces weight and extends vehicle lifetime. With reduction in propellant mass of up to 90% for a satellite designed for 12 to 15 years operation, there is a significant savings in launch requirements. Less propellant results in reduced cost for launch, an increase in payload capability, or an increase in satellite lifetime, or any combination of these. Another application of the high ISP engines is for unloading reaction wheels. The reaction wheel is a system that uses angular momentum to adjust stability in one axis of rotation. As the spacecraft begins to shift because of orbital perturbations, the reaction wheel compensates by spinning up to null out the effects of the new imposed geometry. Eventually a propellant system is required to unload the spinning reaction wheel. Table 1 shows typical thrust values for various different types of engines.

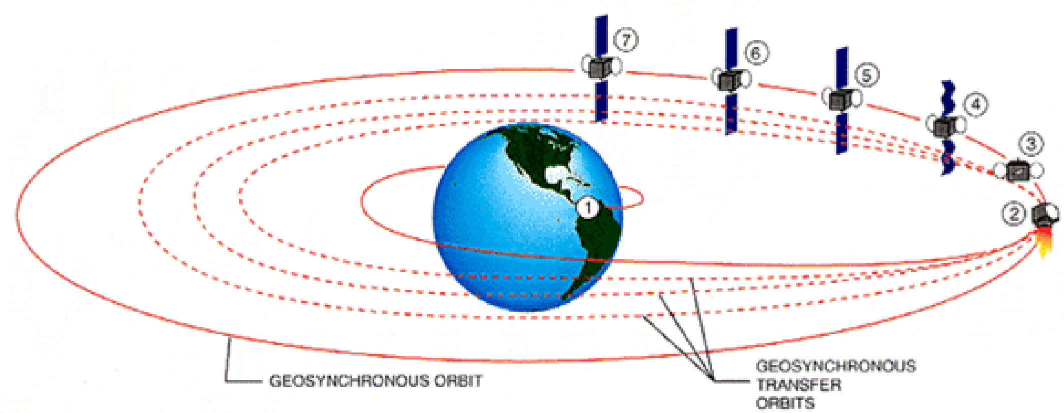

Figure 5 Satellite Launch and Orbit Transfer

As we can see from Table 1, the propellant mass of an ion thruster is much less than 10% of that of a chemical bi-propellant system with 1500% more efficiency.

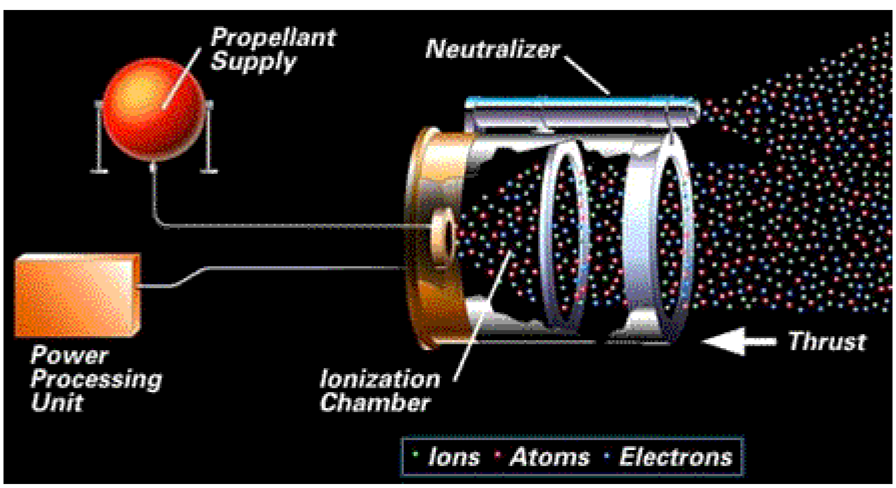

Figure 6 High ISP Ion Engine

Engine	"Ve" eff. exhaust velocity (N·s/kg or m/s)	Specific impulse (s)	Fuel mass (kg)	Energy expended (GJ)	Energy per kg (MJ/kg)
Jet engine	30,000	3,000	50,000	2135	43
Solid rocket	2,000	200	190,000	95	1
Bipropellant rocket	4,500	450	8,200	103	13
Ion thruster	30,000	3,000	620	775	1250
VASIMR	300,000	30,000	100	4,500	45,000
Nuclear photonic rocket	300,000,000	30,500,000	?	?	9×10^{10}

Table 1 Typical Parameters for Engines

The typical GEO Transfer takes an average of 10 days with chemical bi-propellant consisting of three engine burns. In the simplest mode, the transfer would only take one sidereal day. In most cases, orbital transfer takes place after a circular LEO orbit is established, but this is not the only way. When a GEO satellite is launched from the equator, there can be a cost savings by going direct assent to GEO and merely conducting a two-burn orbit transfer. There is however, a significant cost associated with this type of flight. The simplest is not always the cheapest.

The most efficient orbital transfer is called the Hohmann transfer. In this method, depicted in Figure 7there are 3 burns. The first burn is the LEO circularizing orbit burn that takes place immediately upon reaching initial altitude to prevent a free trajectory return to earth and in the case of a satellite a fiery trip into the ionosphere. Once the transfer window is reached, this is the perigee of the orbit required to reach apogee without running into anything, a second burn is initiated to raise apogee from 300 km to 35786.045 km above the mean sea level or to the GEO altitude (42164.2 km measured from the earth’s center). The spacecraft would then proceed along the eclipse until

apogee is reached. Once apogee is reached, a third burn is initiated to circularize the orbit by raising the altitude of perigee to be equivalent to that of apogee. This, very simplified case, assumes instantaneous accelerations with impulse burns. This also assumes that the circular LEO orbit is in the equatorial plane. In reality, unless we launch at the equator, added thrust is required along with the orbital plane change.

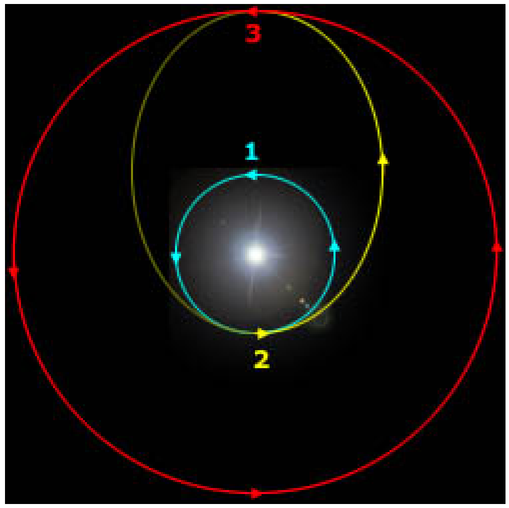

Figure 7 Hohmann Transfer

In the case of the bi-propellant burn, normally the vehicle is circularized in the LEO orbit at 28.5° inclination if launched from Cape Canaveral or at ~5° if launched from French Guyana by the European Space Agency (ESA). Once the window for transfer is reached, an extended burn is conducted which raises apogee beyond the altitude of GEO. There is a cost savings in initiating a plane change and circularizing the orbit at GEO simultaneously. The time of actual thruster burn is just the smallest part of the journey. For the most part the thruster is just a heavy passenger on the spacecraft.

The ion engine weights significantly less and is capable of doing the same job at a significant cost savings. Since the thrust is so low, this form of orbit transfer slowly spirals out to GEO thrusting when not in eclipse of the earth. This is an important note as the batteries would not be able to support the power requirement of continuous thrusting while in eclipse and maintain the spacecraft. The total time of orbit transfer with this method is estimated to take 60 to 90 days depending on the size of the spacecraft. The typical communication satellite on orbit at GEO was about 3500 kg. That number has risen to about 5000 kg today with the increased size of communications satellites. The

weight savings is also conservatively calculated to be a savings of between 4.5 kg and 5.4 kg per day of transfer given a continuous burn on a spacecraft.

With the capability of providing power from the ground while in eclipse, and with a weight savings equivalent to that of the long burn, the trip can be cut to between 20 to 30 days depending on spacecraft mass again. The two-thirds reduction in time is accounted for by the continuous burn and the ability to provide greater power than the sun can.

One argument fielded by the engineers at Loral Space Systems suggests that the degradation on the spacecraft experienced by spending an excessive amount of time in the Van Allen belts would limit the life of the spacecraft. This argument can be refuted by the fact that the entire GPS constellation exists at MEO in the heart of the Van Allen belts. In addition, the degradation experience by the time spent in the strongest of the Van Allen belts has been well measured and documented. It is indeed part of the EOL calculations conducted when sizing a solar array for a specific mission.

The weight savings in using an ion engine versus the chemical bi-propellant is typically 4 to 5 times that of the payload carried. This is accounted for in not only the weight of the engine, but also the significantly heavier fuel. Use of an orbital electric engine for maneuvering saves in the neighbor hood of 5 lbs of bi-propellant per day. While this seems like very little, the continuous use of this kind of propulsion system shown in Figure 8can rapidly account for a major fuel, weight and space savings.

The launch cost of a vehicle from earth to LEO is approximately $5000 per pound. If the typical launch vehicle can be lightened by more than one thousand pounds by divesting the vehicle of the engine and heavier propellant, the up front savings would be more than $5 million dollars per vehicle. The transfer orbit cost from LEO to GEO is around $100 million.

Every year an average of 20 to 25 commercial satellites and 6 military satellites are launched to GEO. In a white paper published by the Futron corporation, launch cost are specifically referred to a cost per pound to orbit as shown in Table 2.[12]

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[12] Futron Corp., "Space Transportation Costs: Trends In Price Per Pound To Orbit 1990-2000," 6 September 2002, <http://www.futron.com/pdf/FutronLaunchCostWP.pdf>, (May 2006).

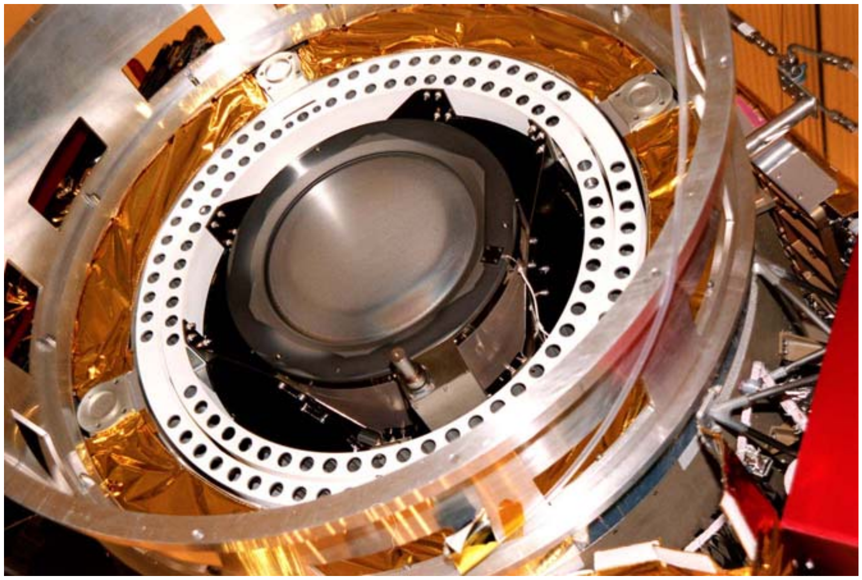

Figure 8 Boeing-Hughes Ion Engine[13]

In the year 2000, the average associated launch cost was around $100 million per launch. With a total annual launch averaging at about 29 satellites, this easily adds up to over a $2.9 billion in just launch costs each year. The second way Futron calculates the launch cost per pound exceeds the low estimate five fold. In the second estimate, annual launch costs are calculated to be $14.5 billion in launch costs alone for the year 2000. In the long run, a power beaming system could provide significant cost savings in reducing launch costs by allowing orbiting satellites to operate longer relieving the need for so many launches. Even at a cost saving of one launch a year, there would be between $125 million and $500 million to apply to orbiting satellite maintenance.

Table 4: Average Price Per Pound for Western and Non-Western Launch Vehicles

Vehicle Class	LEO		GTO	
	Western	Non-Western*	Western	Non-Western*
Small	$8,445	$3,208	$18,841	N/A
Medium/Intermediate	$4,994	$2,407	$12,133	$9,843
Heavy	$4,440	$1,946	$17,032	$6,967

* The Zenit 3SL is considered a non-Western launch vehicle because of its Ukrainian and Russian heritage.

Table 2 Average Price Per Pound for Launch Vehicles[14]

13 Boeing, "Factsheet: Image, Close-up of Hires-Xenon Engine,"<http://www.boeing.com/defense-space/space/bss/factsheets/xips/nstar/closeup_hires.jpeg>, (April 2006).

14 Futron Corp., "Space Transportation Costs: Trends In Price Per Pound To Orbit 1990-2000," 6 September 2002, <http://www.futron.com/pdf/FutronLaunchCostWP.pdf>, (May 2006).

5. Orbit Maintenance / Station Keeping

Once on orbit, chemical bi-propellants and monopropellants like hydrazine are required for orbital maintenance and station keeping. Here again high Isp engines can provide for the necessity while reducing the mass and storage requirement.

a. Correct for Orbital Perturbations

Newer systems use a host of electrical systems like momentum wheels and reaction wheels to maintain attitude. These articles use electrical power up to a point. Once a momentum wheel has reached a certain RPM, an onboard propellant must be expended to slow or stop the loaded reaching without losing the attitude adjustment. This job can also be taken care of using an electric engine. The power budget for this type of system requires resources that would otherwise be used in the normal operation of the satellite. Provision for excess power beamed from the surface would nicely allow for these types of maneuvers.

b. Eliminate or Reduce Need for Hydrazine Thrusters

With the use of high Isp engines, dangerous chemical systems like hydrazine, which is also highly corrosive and requires special precautions and handling, can be eliminated. This reduces the possible hazard of flight criteria for the satellite also.

c. Change Subsatellite Point

One mission a satellite may be called to do from time to time is the changing of the subsatellite point. The subsatellite point is the satellites ground track with respect to the surface of the earth. For a perfectly geostationary orbit, this would be a point on the surface. For a geopositional satellite, one that is at the same altitude but at a slightly inclined orbit, the subsatellite point is a figure eight ground track. To change this subsatellite point, the vehicle must change its velocity in its orbit. If the satellite must move forward along its orbit, it must first fire its thrusters in the direction of travel that will actually speed up the orbit by reducing the vehicles altitude. This is reversely intuitive, as one would think that pushing should be done while the front of the spacecraft

pointed in the direction that the satellite wishes to travel. Once the new subsatellite point is reached, the spacecraft reorients in the direction that it has been traveling and executes a second burn to add energy to the vehicles orbit, slowing it down and placing it in a new GEO orbital position. The opposite is true for moving backward along an orbit. The spacecraft must first raise its orbit to slow and then lower it to speed into position.

d. Changing Mission Requirements

The provision of power beaming can be vital to supplying power to a spacecraft with a changing mission requirement. The vehicle may not have the resources otherwise to complete its new tasking.

e. Space Control: Evasive Maneuvers

Space is a hostile environment and there are many thousands of objects floating around at incredible speeds on their elliptical orbits. To avoid collision or reduce the possibility of collision the spacecraft may be required to take an evasive maneuver to allow a less controllable mass to pass clear of our asset. In addition, a new orbit may be required as previously undiscovered situation may arise requiring an evasive maneuver. This maneuver may require more power that the vehicle is able to provide. Power beaming with its greater conversion efficiency, may be capable of providing the extra required power.

f. Electric Propulsion Ideal

As a weight savings measure, spacecraft of the near future may be designed and constructed without bipropellant engines relying solely on electric propulsion. The spacecraft bus with an optimum design will require power beaming to supplement the sun’s effects and provide the extra power required for maneuvering.

g. Laser Power Can Cut Maneuver Times In Half

When orbit is to be changed using high Isp engines alone, the onboard solar panels have to provide all the power the thrusters require. Power beaming can

provide to benefits that the sun alone cannot. First, the coherent and conditioned power can be transmitted at a higher power and higher power efficiency transfer ratio. Second, the power can be provide through eclipse saving around a third of the time required to raise the orbit with solar power alone.

h. Laser Power Can Enhance Solar Flux

Solar energy changes cyclically over a 22-year cycle with a high at solar maxim and a low at solar min. Additionally, the sun experiences solar flairs that are huge explosions of energy releasing millions of tons of atomic matter and energy that influences the satellite in its orbit causing power spikes and orbital perturbations. Power beaming can be used to null the effects experienced by the spacecraft by active controls.

6. Orbital Maneuvering

Previously we discussed the use of high Isp engines for station keeping, orbital maneuvering and system unloading. Another use for power beaming could be to provide energy to a solar tug.

a. On-orbit Servicing, Refueling, Inspection

The solar tug concept has been proposed many times and is not new. A solar tug would be a spacecraft placed on orbit for the purpose of collecting ailing, dying, and dead satellites and spacecraft and bringing them down from higher orbits for collection and servicing by a vehicle such as the space shuttle or the space station, or for disposal in the earth atmosphere. With space becoming so cluttered, this concept will take more precedence. Power beaming could provide the tug with its power to continue its operations.

7. Solar Panel Annealing

Solar panel annealing is one of the most exciting possibilities for power beaming. Annealing of degraded solar cells realigns the lattice structure of the solar cell, a process that has been thought of as analogues to combing. In this application, the solar array would in a reverse bias condition, receive excess power above that nominally received

from the sun, which would have the effect of even a modest increase in capacity in repairing degradation due to solar radiation. If conducted annually for even as little as an hour, a solar array on orbit could regenerate its capacity to about 99% of BOL values. While this has never been tried in space, laboratory experiments have shown that it cyclic annealing can restore solar cells. End of life annealing is not nearly as successful. Long exposure has only resulted in minimal annealing benefit. A satellite that undergoes the annual annealing from the BOL, could theoretically orbit until limited by the degradation of another system.

The onboard batteries can also use this enriched current source to repair themselves to some degree, extending the life of the orbital platform. The degradation comes from trapped energetic particles that break down the crystalline structure of semiconductor material and degrade the solar cell performance. Some orbits are worse than others are. Mostly the orbits between 1000 km and 50,000 km have the worst radiation damage. The process of annealing can repair this damage and prolong the mission life. Many satellites reach end of life due to insufficient power. This could be the expiration of the batteries, but it could also be the inability of an exposed solar array's inability to produce the required energy due to excess electron and proton damage.

C. ALTERNATE USES FOR POWER BEAMING

Using lasers to measure distances and for tracking is also a form of power beaming, though this purpose uses significantly less power. This process can be conducted simultaneously as the incident beam is being employed for use with an on-orbit platform a small amount of reflected energy could be used to track, focus, and adjust the beams intensity to provide the maximum and most efficient benefit.

One possible use would be to power a remotely located vehicle on the surface of a heavenly body like the moon while the vehicle is in eclipse or in a crater. Battery power may not be sufficient in this context requiring additional power from a remote site. In this eventuality, wire or fiberoptic transmission may be a costly or not a realistic way of energy transmission. A beam of energy directed from the crater rim to the vehicle in the crater is a very cost effective and realistic way of providing power. The laser itself need not be on the rim. Current technology will allow remote beaming of power that can be

redirected to the remote vehicle, Figure 9As fanciful as this concept might appear to be, if the moon is ever to be colonized, the most precious resource will be water that may exist in the moons southern impact crater. Flights of fancy, such as lunar prospecting, might become a reality with the projected 2020 return to the moon.

A current use for power beaming technology, though not terrestrial based, in use today is in communication between orbiting satellites. This is done at a little lower frequency (around 60 GHz) than we will be concerned with. Energy is modulated within the power beam and directed at a know receiving satellite. The transmission bandwidth can be large with high throughput and little probability of error in the vacuum of space. Sixty giga-Hertz is an ideal center frequency as it is not a frequency that can be readily interrupted by terrestrial effects. Electromagnetic radiation is almost completely absorbed by atmospheric effects limiting terrestrial application. This factor completely negates the use of this area of the spectrum for ground to space transmissions and makes it the ideal heavenly frequency with which to communicate or cross-link data.

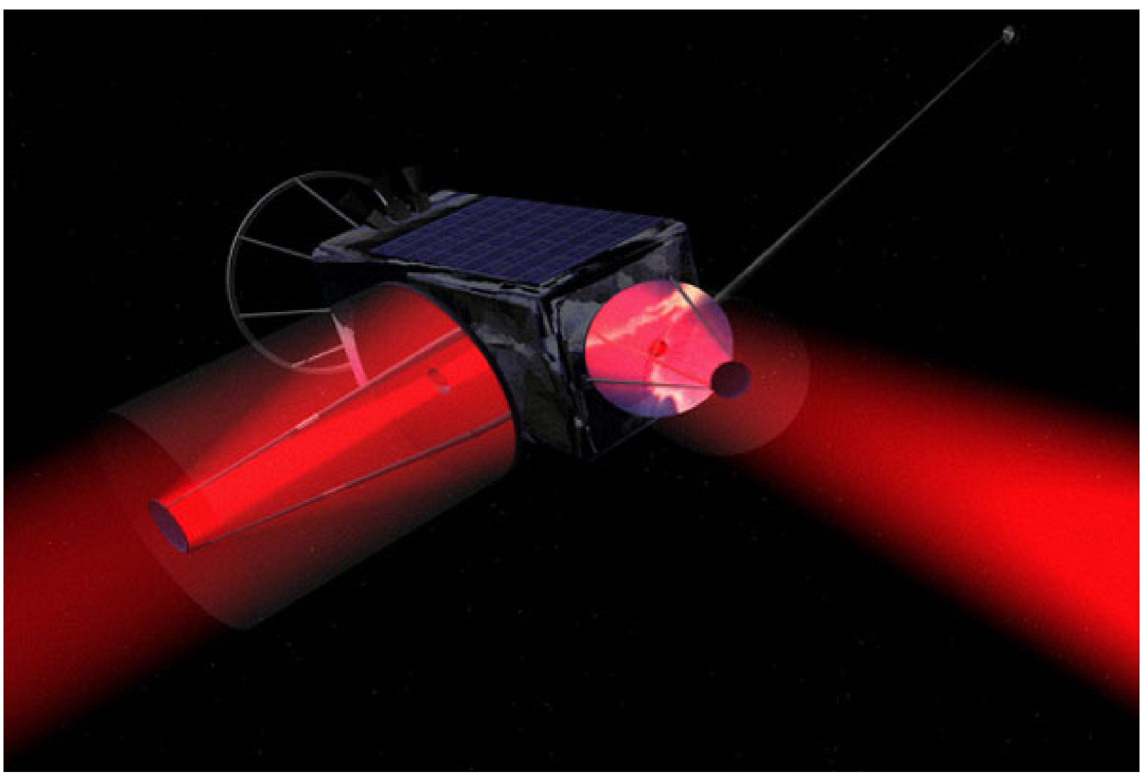

Figure 9 Artists Concept of a Space Based Relay mirror

There are two basic schools of thought in power beaming, those that consider the propagation of microwaves (masers) and those that focus on propagation of higher frequencies (lasers). We will discuss microwaves, masers, lasers and gyrotrons in the next chapter.

D. SUMMARY

Power beaming from the ground will save satellite mass, complexity, and cost. It will provide unique capability like excess power availability, power in eclipse, and annealing to enhance and extend mission payloads. One major benefit of power beaming besides the unique capabilities it provides will be to lower launch costs by reducing payload size and weight. It will provide higher satellite reliability by reducing onboard system requirements and by providing maintenance effects. Finally, power beaming provides the satellite community the real possibility of longer satellite lifetimes that will mean multimillions in cost saving measures. The trade off for these real possibilities will be the need for the construction of seven dedicated ground-based sites for maximum coverage with the most efficient orbital coverage.

The remaining chapters of this argument will discuss the mechanics of power beaming from the science of beam generation through optics and telescope propagation to solar cell basics and on-orbit power conversion. The final two chapters will discuss a proposed experiment and possible follow-on work.

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III. LASERS

A. CHAPTER OVERVIEW

While the title of this chapter is lasers, this chapter will cover multiple concepts that deal with lasers. The concepts of electromagnetic (EM) wave propagation and associated terms are integral and will be discussed in some depth. A discussion of forms of energy propagation and the three general types of lasers will lead to a discussion of what laser current suits our purposes. Finally, we will briefly look at what laser technologies and products are available for the purpose of our investigation.

B. APPICATION TO POWER BEAMING

Lasers are the beginning of a system that will provide power to the satellite. Lasers concentrate electrical energy by various methods. These methods, grouped into three general areas of generation, provide a coherent, energetic source of light that is projected in a single direction. To see a laser off axis, some form of diffraction or reflection must occur. This can be thought of as a form of energy loss from the laser beam. The laser must also operate in the visible light spectrum. Since all lasers do not necessarily operate in the visible spectrum we will also discuss the electro magnetic spectrum to get an understanding of what lasers are and how they apply to power beaming.

C. ELECTROMAGNETIC SPECTRUM

(EM) radiation is the basis for all electrical power. Other forms of energy exist such as fluid energy, thermal energy, chemical energy and other forms of potential and kinetic energy, but mainly for the purposes of our discussion of power beaming, we will focus on electromagnetic forms of energy for storage and transmission. Figure 10, Figure 12, and Figure 12 show the majority of the electromagnetic spectrum measured and represented in various ways. The importance of this will become apparent as we will talk about it extensively in this argument referring to in all three ways that it is measured. For

instance, when talking about optical lengths we will use wavelength, but when talking about solar cells we will discuss the EM spectrum in the form of electron Volts (eV).

The electromagnetic spectrum has no upper or lower limit of frequencies. It extends from the theoretical length of the universe down to Planks' Constant (*h*). For the purposes of our discussion, we will look at the wavelengths shown in Figure 10

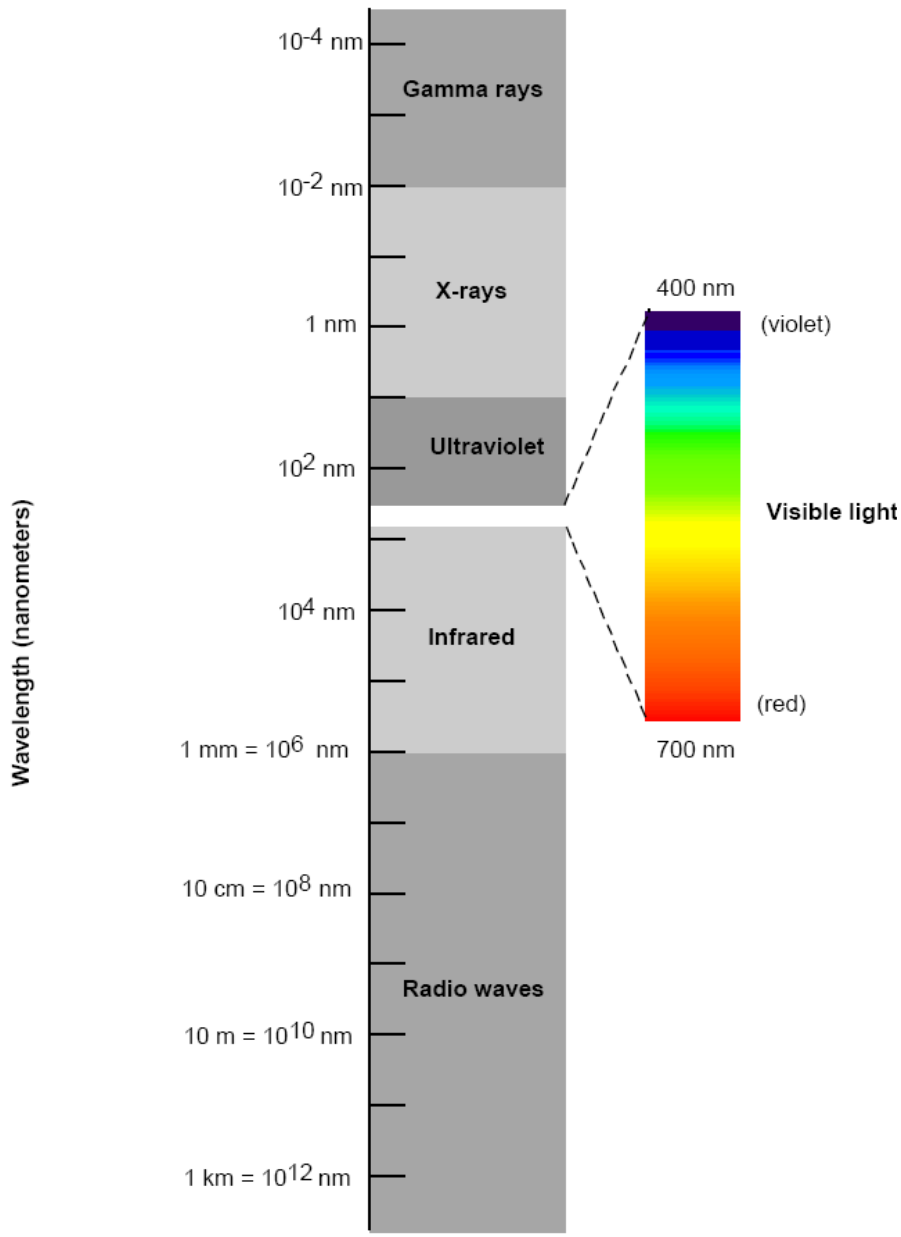

Figure 10 Electromagnetic Spectrum

As alluded to before, EM radiation can be discussed in one of three ways: as a wavelength (λ), as a frequency (*f*), or as a photonic energy (*E* or eV). The conversions are shown in Figure 11 When being discussed as a frequency, a common conversion is to discuss frequency in terms of a ratio (dB). Frequency is normally expressed in Hertz (Hz), which represents cycles per second. To covert from Hertz to ratio, one must take the logarithm to obtain the decibel representation, see Equation (3.1).

$$dB = 10 \times \log_{10}(Hz) \tag{3.1}$$

There is a simple relationship between the frequency of oscillation and wavelength of electromagnetic energy, see Equation (3.2).

$$\lambda = c / f \tag{3.2}$$

Figure 11 EM Spectrum Showing Frequency vs. Wavelength vs. Energy

Nearly all things in the universe emit, reflect, or transmit some light energy. A classification system was derived to categorize the different energy levels. Figure

13shows the grouping of the different energy bands. We will only mention these groupings. For a more intense study, see the reference dealing with the EM Spectrum.

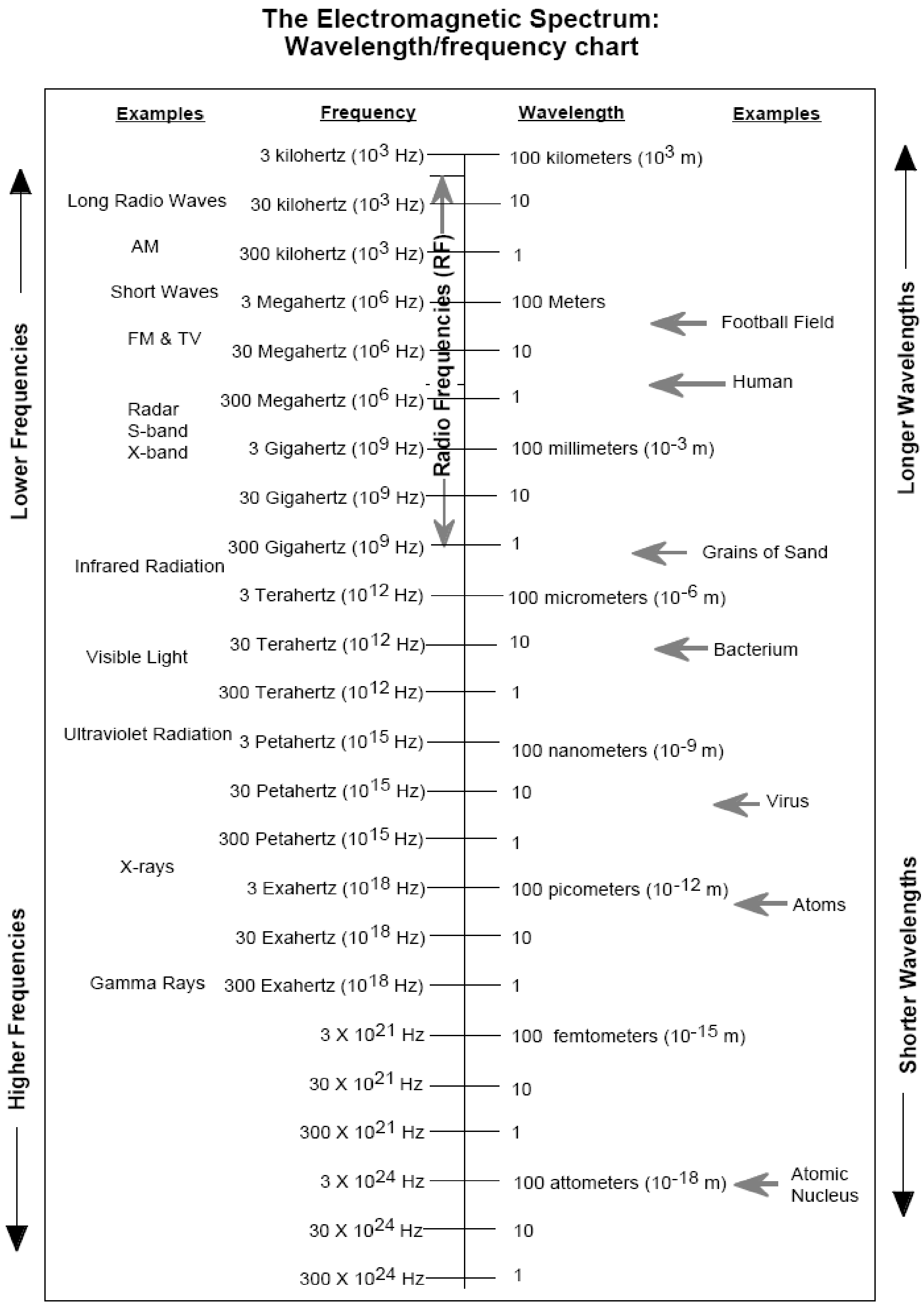

Figure 12 Electromagnetic Spectrum

The classifications of the EM spectrum are generally accurate, but in some cases predate the development of a universal definition, which accounts for some overlap in the definition of thresholds for the individual areas. Some of these definitions are based on how different frequencies of the same phenomenon act. For example, some low-energy gamma rays actually have shorter wavelengths than some of the high-energy X-rays. This is because the distinction between X-rays and gamma rays is related to the energy source rather than the definition of the spectrum.

1. Microwaves

Microwaves are at the upper end of the Radio Spectrum that extends from 3 Hz to 300 GHz. They extend from 3 GHz to 300 GHz. Microwaves are EM waves generally short enough to be employed in waveguides. Microwave energy is produced by klystrons, magnetrons, and some diode devices.

2. Terahertz Radiation

This region is only defined by its frequency. It is located between the upper microwave and the far infrared from 300 GHz to 3 THz. Its important to power beaming is slight though, as this is potentially the low end of our laser use with power levels from 1.24 meV to 12.4 meV, it may become very important. While these low levels won't necessarily transport energy at levels large enough to excite electrons above the bandgap, discussed later, they are the levels that we would consider for measuring atmospheric affects that will become more important later as we talk about optics. There are few current uses for EM radiation in this band though some wireless networks are exploring using this long-range enhancement capability to extend their Wi-Fi networks. This is also the range at which military development is researching ways to project energy that will incapacitate its opponents without potentially being lethal.

3. Infrared Radiation

Infrared extends from 300 GHz to 400 THz. The lower part of the range is actually called microwave based on absorption characteristics. Water absorption in this

range is so intense that the atmosphere is seen in this region to be effectively opaque. This is actually of interest to our applications using optics. We will discuss this more in the next chapter.

The region is effectively further broken down into three sub regions: far, middle and near infrared. The far infrared is the lowest wavelength. The middle infrared is often called the finger print region, as the absorption spectrum is very specific to each individual compound. The near infrared actually should be considered visible light though we cannot detect wavelengths this high with our eyes. The near infrared actually has many of the same characteristics as visible light. Many low light devices actually utilize this range.

4. Visible Light

Visible light is electromagnetic radiation at frequencies that can be sensed by the human eye. It is a generally held concept that the eye developed the way it did to capture the electromagnetic spectrum. This is also the spectrum that the sun and many of the stars like ours emit most of their radiation energy. Visible light is typically absorbed and emitted by electrons in atoms as they move from one energy state to another.

5. Higher Order EM Radiation

Above visible light comes the ultraviolet, X-ray and Gamma ray radiation. All of these types of radiation are so energetic that they do not just add enough energy to the electrons to move between adjacent levels, they actually can physically change the entire composition of the atomic structure freeing electrons and when energetic enough, breaking the strong nuclear forces. They are noted for breaking the chemical bonds of molecules and are more disruptive then useful.

All electromagnetic waves propagate at the speed of light (2.998×10^8 m/s) in free space or a vacuum. The wavelength of a single oscillation of electromagnetic radiation is defined as the distance the wave will propagate in vacuum during the time required for one oscillation.

6. Waves or Particles

Electromagnetic energy of all frequencies or energies can be viewed in physics as if it were waves, as described above, and as particles, known as photons. It is generally common to speak of waves when talking about lower frequencies and longer wavelengths. References to photons are common for conversations discussing light and electromagnetic forces of higher frequencies or energies. Waves are described in terms of frequency, wavelength, and amplitude. Photons, seen as particle carriers of the electromagnetic force, are described in terms of energy level using the electron Volt (eV).

D. INVERSE-SQUARE LAW OF PROPAGATION[15]

Electromagnetic radiation normally propagates in straight lines at the speed of light and does not require a medium for transmission. It slows as it passes through a medium such as air, water, glass, and other denser materials. Another property of the movement of EM radiation is its expansion. If directionality is momentarily ignored, propagation would be seen as an ever-expanding sphere. Applying directionality, Figure 13depicts the expansion of radiation as it transits the direction of travel. The expansion accounts for the diffusion of energy over distance. The energy remains constant in a vacuum, but it spread out over a greater area. This area increases proportionally to the square of the distance the radiation travels. The area of this expanding sphere is calculated as $4\pi r^2$. This relationship is known as the *inverse-square law* of propagation. It accounts for loss of signal strength over space, called space loss.

As an example, Saturn is approximately 10 times farther from the sun than is Earth. The energy received on earth by the sun is 1366.1 W/m^2. The energy received at Saturn is only 15.04 W/m^2. Therefore, By the time the sun's radiation reaches Saturn, it is spread around 100 times the area it would have covered at Earth's distance from the sun.

15 Susan Watanabe, Jet Propulsion Laboratory, "Inverse-Square Law of Propagation," <http://www2.jpl.nasa.gov>, (Jan 2006).

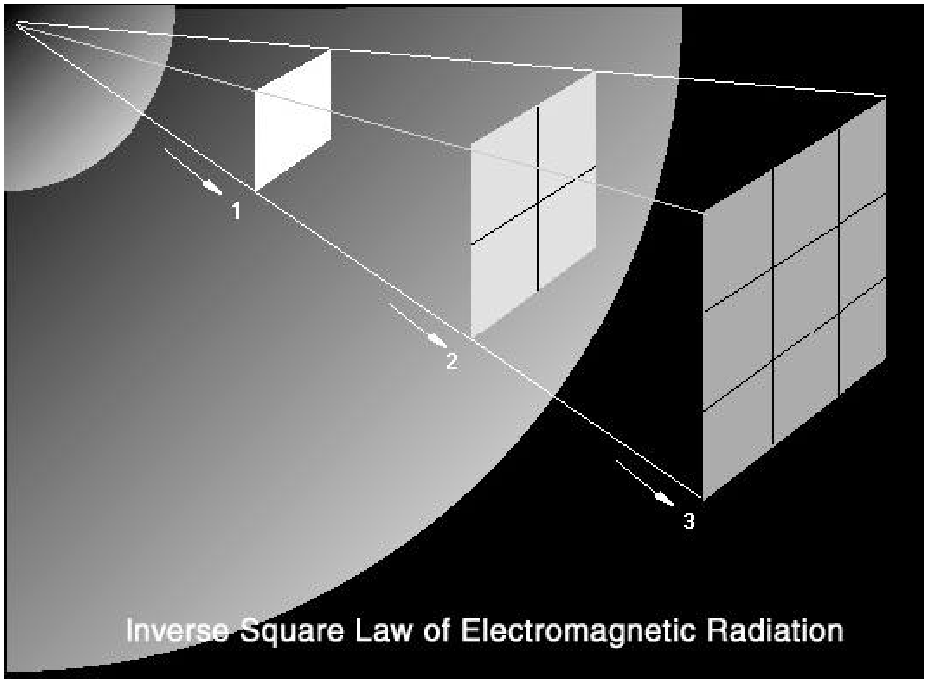

Figure 13 Electromagnetic Spreading

E. DIFFRACTIONS LIMITS

Laser propagation over relatively short distances experiences very little spreading. When that beam is broadcast over infinite space, it experiences spreading in accordance with the Inverse-Square Law of Electromagnetic Radiation.

> A wave does not have to pass through an aperture to diffract; for example, a beam of light of a finite size also undergoes diffraction and spreads in diameter. This effect limits the minimum size *d* of spot of light formed at the focus of a lens, known as the *diffraction limit*:[16]
>
> $$d = 2.44\lambda\frac{f}{a},$$
>
> where λ is the wavelength of the light, *f* is the focal length of the lens, and *a* is the diameter of the beam of light, or (if the beam is filling the lens) the diameter of the lens.

This indicates what is known to be true about a wave front. The wave front does not not spread evenly. In fact, the wave front actually is more intense at the point of incidence and diffuses as it moves away from center as shown in Figure 14

[16] Dick Lyon, Wikipedia,Wave Mechanics: Diffraction, "Diffraction Limit," 12 April 2006, <http://en.wikipedia.org/wiki/Diffraction_limit>, (Apr 2006).

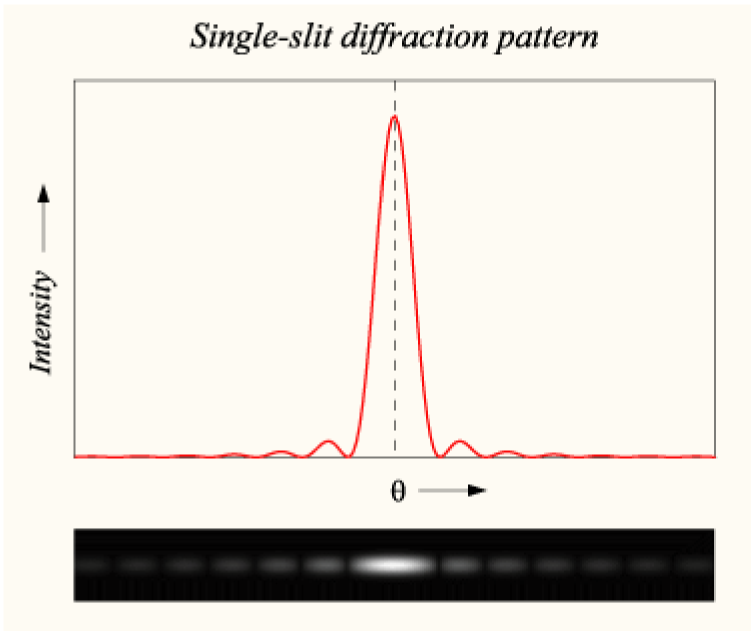

Figure 14 Single Aperture Diffraction[17]

1. The Maser

Masers (microwave amplification by stimulated emission of radiation), involve the interaction between an electromagnetic wave of a certain wavelength and an atom or a molecule in an excited energetic state. The passage of the wave triggers the atom to give up energy in the form of more radiation of exactly the same wavelength. This reinforces the passing wave, which can then interact with more excited atoms to build up a well-directed, intense pulse of monochromatic radiation. It has high power at millimeter wavelengths because its dimensions can be much larger than the wavelength, unlike conventional vacuum tubes, and it is not dependent on material properties, as conventional masers. The bunching depends on a relativistic effect.

2. The Gyrotron

The gyrotron is a type of free electron maser. The maser is a source of very intense, narrow-band, coherent microwave radiation.[18] The electron speed in a gyrotron

[17] Dick Lyon, Wikipedia,Wave Mechanics: Diffraction, "Diffraction Limit," 12 April 2006, <http://en.wikipedia.org/wiki/Diffraction_limit>, (Apr 2006).

[18] David Darling, "The Encyclopedia of Astrobiology, Astronomy and Spaceflight," <http://www.daviddarling.info/encyclopedia/M/maser.html>, (Jan 2006).

is slightly relativistic (comparable to but not close to the speed of light). This contrasts to the free electron laser which works on different principles and whose electrons are highly relativistic.

3. The Laser

A laser[19] (light amplification by stimulated emission of radiation) is a device that uses a stimulated emission, which is a quantum mechanical effect, to generate a coherent beam of light. A laser device includes a power source, a gain medium and mirrors that form an optical resonator. The light generated is monochromatic**.** It contains one specific wavelength of light (one specific color). The wavelength of light is determined by the amount of energy released when the electron drops to a lower orbit.

With current efficiencies, lasers are employed in a host of non-traditional areas such as consumer electronics, medicine, and information technology. Laser ring gyros keep ships on course.

Lasers create light by raising the energy level of atoms in a medium. This energy is stored by the atom in its outer electron belt by raising the energy level of its valence electrons. Once an electron moves to a higher-energy orbit, it eventually wants to return to the ground state. When it does, it releases its energy as a photon, a particle or quanta of light. Anything that produces light does it through the action of electrons changing orbits and releasing photons.

In a laser the light generated is coherent. It is organized, meaning each photon moves in step with the others. This means that all of the photons have wave fronts that launch in unison.

The light is directional. A laser light has a very tight beam and is very strong and concentrated. A flashlight, on the other hand, releases light in many directions, and the light is very weak and diffuse.

There are three categories of lasers: Chemical lasers, Solid-state lasers (SSL) and Free Electron Lasers (FEL). The categories themselves are further separated into smaller units, but those definitions vary by author. In discussing these lasers, we will begin with the largest, the FEL, and work our way through to the smallest, the SSL.

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19 Naconkantari, Wikipedia, Energy Development, “Xaser,” 8 Janruary 2006, <http://en.wikipedia.org/wiki/Xaser>, (Jan 2006).

Lasers are never visible in a vacuum. Only when pass threw a medium such as air containing dust do we see a Rayleigh scattering or Raman scattering. With the higher intensity beams, the air can heat up to the point that it becomes plasma, which would be visible. This is however, potentially damaging to the source laser.

F. FEL

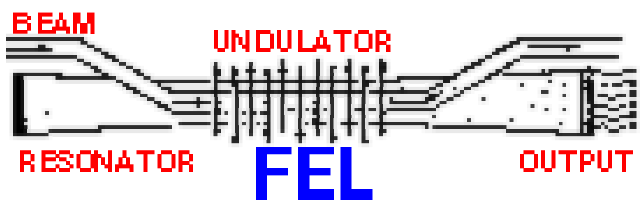

Figure 15 Diagram Of A Free Electron Laser

The Free Electron Laser or sometimes-called Xasers are the largest class of the laser family in shear size. It is not uncommon to talk about the physical size of a FEL in football fields or miles. Figure 15depicts a FEL.

A Free Electron Laser generates tunable, coherent, high power radiation, capable of spanning wavelengths from millimeter wavelengths to the visible and potentially ultraviolet to x-ray. It generally has the optical property characteristics of conventional lasers such as high spatial coherence and a near diffraction limited radiation beam. It differs from conventional lasers in using a relativistic electron beam as its lasing medium, as opposed to bound atomic or molecular states, hence the term free-electron.

A free-electron laser requires a linear electron accelerator (LINAC) and a long wiggler section of alternating magnets. This type of technology has been referred to a solution for which the question has not been formulated.

This is a large laser that operates in and very much above the power output requirements of power beaming. Typical quoted values range from the 10s of keV to will into 1.2 GeV, well above the power beaming useful range.

G. CHEMICAL LASERS

Chemical lasers are powered by a chemical reaction. It uses an exothermic (energy liberating) reaction as an energy source to pump a low-pressure gas phase gain medium. Chemical lasers are usually large, high power devices that integrate chemical delivery systems, a supersonic nozzle and an optical resonator. They require specialized fuels and exhaust waste heat. When operated continuously, they can develop very high powers.

One subcategory of chemical lasers that most people are familiar with are the excimer lasers. Excimer lasers, derived from the terms excited and dimmers use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton or xenon, to produce a lasing effect that does not heat the medium in which it travels. When electrically stimulated, a pseudo molecule, dimmer, is produced that, when lased, produces light in the ultraviolet range.

Excimers emit a very tightly focused beam of ultraviolet light. The ultraviolet light is absorbed by the upper layer of the surface that it contacts. The sheer amount of ultraviolet light is too much for most organic materials to absorb, resulting in the breakdown of the molecular bonds of the material.

The ultraviolet beam of light only penetrates a microscopic amount, less than a nanometer. When in contact with organic material, heat created is dissipated along with that layer of the material. This process is known as photo ablation.

This type of laser is considered a very low energy laser and has very little application in power beaming. The high energy types of chemical lasers have only relatively short duration beams which consume the medium as a product of lasing. This makes their application limited in power beaming, though they are a proven technology of sufficient power for our application. Reuse becomes the problem with this type of technology.

H. SOLID STATE LASERS

The Solid State Laser (SSL) uses a solid crystalline material as the lasing medium. There are really two types of solid-state laser, the electrically pumped and the optically pumped. Both types use very intense flashes of light or electrical discharges pump the lasing medium and create a large collection of excited-state atoms. A large collection of atoms in this super excited state will cause a laser to work more efficiently. In general, the atoms are excited to a level that is two or three levels above the ground state. This increases the degree of population inversion. The population inversion is the number of atoms in the excited state versus the number in ground state.

Once the lasing medium is pumped, it contains a collection of atoms with some electrons sitting in excited levels. The excited electrons have energies greater than the more relaxed electrons. Just as the electron absorbed some amount of energy to reach this excited level, it can also release this energy.

This emitted energy comes in the form of photons, see Figure 16. The photon emitted has a very specific wavelength that depends on the state of the electron's energy when the photon is released. Two identical atoms with electrons in identical states will release photons with identical wavelengths.

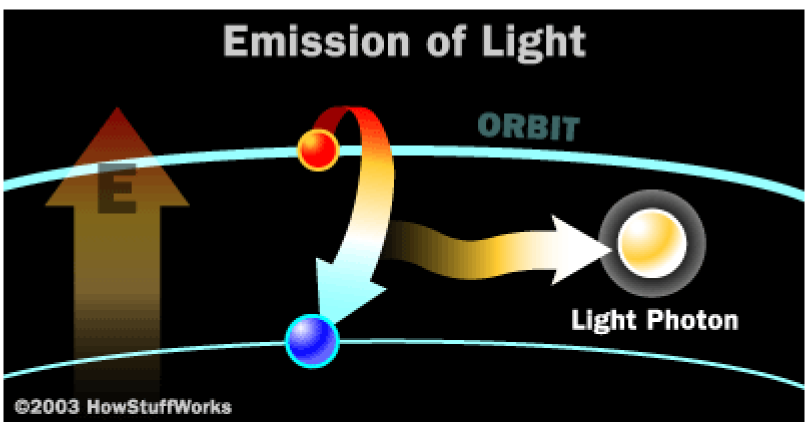

Figure 16 Photon Emission [20]

[20] Mathew Weschler, " How Lasers Work," <http://science.howstuffworks.com/laser3.htm>, (May 2006).

1. Optically Pumped

The original SSL, the ruby laser, invented in 1960 was of the optically pumped type. Some references consider the electrically pumped type of SSL as an entirely different category. For our purposes, we will discuss them as SSL, as they operate similarly on basic principle.

In the SSL, in the optical case, energy is pumped into a rod that has mirrors at both ends, one being semi-permeable. Photons, with a very specific wavelength and phase, reflect off the mirrors to travel back and forth through the lasing medium. In the process, they stimulate other electrons to make the downward energy jump and can cause the emission of more photons of the same wavelength and phase. A cascade effect occurs, and soon we have propagated many, many photons of the same wavelength and phase. The mirror at one end of the laser is "half-silvered," meaning it reflects some light and lets some light through. The light that makes it through is the laser beam.

The rod is made of a material that was originally chromium doped aluminum oxide (synthetic ruby rod). The intense energy liberates some of the chromium atoms to an upper state of energy. The intense pulse of coherent red light is then emitted through the small aperture on the semi-permeable end of the tube. The energetic beam contains enough energy to cut through thin metals. After its discovery, this type of laser was thought to be of the type that that science fiction had proposed for laser guns.

Today, modern optically pumped lasers use Yttrium Aluminum Garnet (YAG) and neodymium doped (ND) materials in much the same way as the original ruby lasers. These types of optically pumped lasers have much lower thresholds of lasing and other desirable physical and optical properties. These lasers typically operate between 1000nm and 2800 nm, must at the lower region. These lasers account for the low and medium power lasers up to just a few watts.

2. Electrically Pumped

Depending on the source you read, electrically pumped lasers or diode lasers are or are not considered SSL. For the purposes of our discussion, we will include them in the SSL. A diode laser uses a p-n junction operating in forward bias to inject electron-

hole pairs into a semiconductor to create light. They are traditionally very small and use low power. They may be built into larger arrays for greater power. Though there is no limit to the number of diode lasers that can be chained theoretically, heat dissipation becomes a problem with higher power arrays. Even the largest arrays to date do not provide the output power requirement for power beaming though some are getting much closer.

The best flash lamp-pumped Nd: YAG lasers have efficiency, relating electrical input to laser output, of about 6%. The electrically pumped, Diode-pumped Nd: YAG lasers have roughly double this efficiency as they operate more directionally. Laser diodes have relatively high efficiency (about 45 to 50% DC to laser power depending on the reference) and are inherently lightweight. Further, the output wavelength of 800 to 900 nm is very close to the peak response wavelength for existing solar cells, which would be good if future arrays could be chained to produce power levels up to 1.4 eV or better at sustained higher wattages. Though today it is not the laser of choice for power beaming, continued rapid development in this area of lasers holds the most promise for providing the power levels we require in the near future.

The most sited reference on solid-state lasers was Sam's Laser FAQs, which deals mostly with safety and implementation, but contains a surprisingly good amount of material on solid-state laser state of the art technology.[21]

I. MILITARY LASER PROGRAMS

This topic is of importance because it is driving the production of the highest energy lasers. Typical operational programs are using Chemical lasers, but an extensive amount of research is also focused in higher-powered SSLs.

The two chemical lasers in the power levels required are the Air Force's Airborne Laser (ABL), see Figure 17 and the Army's ground-based Tactical High Energy Laser (THEL), see Figure 18The ABL was designed to shoot down ballistic missiles and the THEL was designed for defense against rockets, mortars and artillery shells. These technologies, being impractical for battlefield operations, are taking a back seat to

[21] Samuel M. Goldwasser, "Sam's Laser FAQ," Copywrite 1994-2006.

emerging SSL technologies in many funding areas. While the technology lags the chemical lasers in power levels, working models are on the horizon.

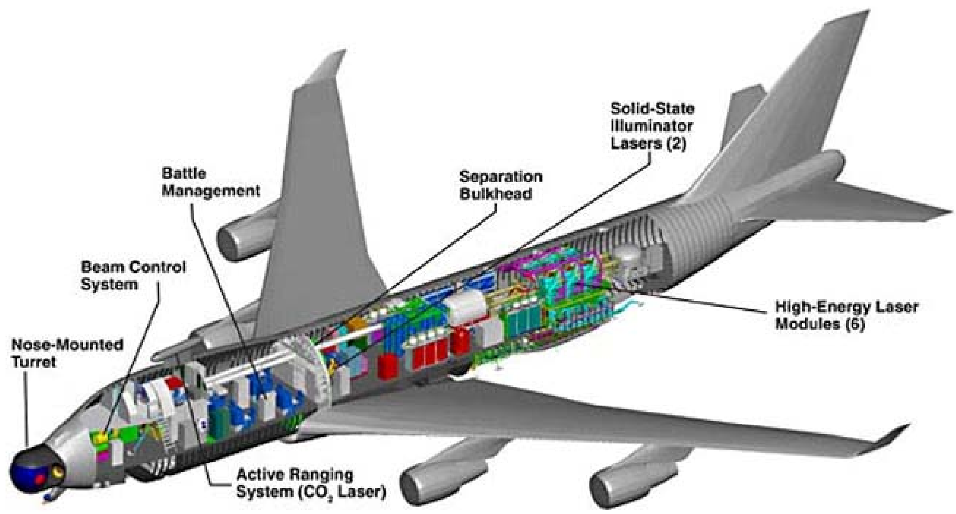

Figure 17 Current ABL Platform

Figure 18 Artists Concept of aTHEL in Operation

Companies like TRW and Raytheon now claim that a 25 kw SSL is achievable and that, within five to ten years power levels up to 100 kw will be available. The technological concerns remain, not the chaining of SSL to create more powerful systems, but with heat rejection and dissipation built up in the lasing cavity. Heat remains in the laser medium, increasing the temperature of the substrate until lasing with acceptable beam quality is impossible. Another milestone is to generate optics rugged enough to withstand high power levels for long periods of time without thermal breakdown.

J. SUMMARY

In this chapter, we discussed the electromagnetic spectrum, some important concepts of energy propagation and about the many types of lasers. We provided measurements of what type of power and spreading that we could expect when delivered to an orbital vehicle. We concluded that power beaming is entirely possible with current technologies.

While many lasers have low conversion efficiency, power is extremely cheap on Earth compared to the cost of power in space, making the possibility of providing power to orbit using the technologies and systems previously discussed.

In the next chapter, we will discuss the subject of optics. This topic is important to our argument, because optics will play an integral role in providing the most efficient energy transfer from the laser to the satellite.

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IV. OPTICS

A. CHAPTER OVERVIEW

In this chapter, we will look at the science of optics. Optics are very important to our study and in optics is the relatively new field of adaptive optics which has come into some maturity recently allowing astronomers to finally see far-field objects with incredible angular resolution or image quality. Advance optics allows ground based telescopes to complete in clarity with the Hubble space-based telescope, Figure 19Before we can jump right into adaptive optics, we must first look at what was done previously that lead to the need for adaptive optics.

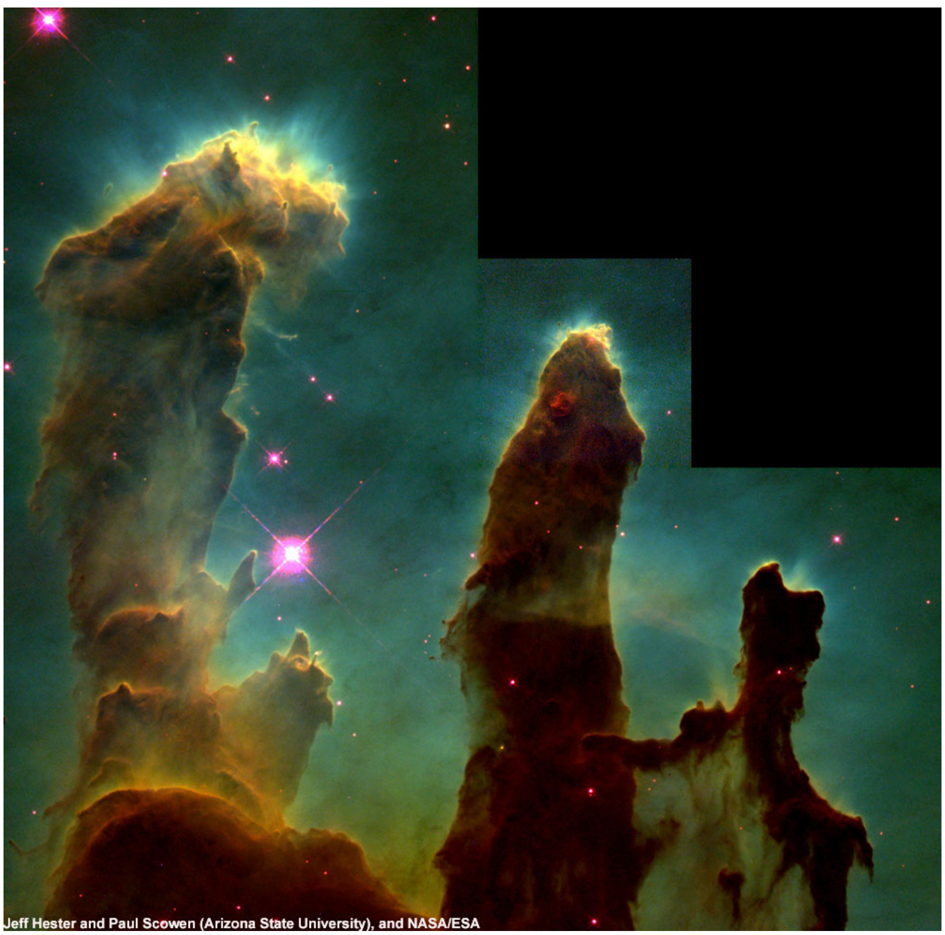

Figure 19 Picture taken with the Hubble Space Telescope using Adaptive Optics

B. APPLICATION TO POWER BEAMING

The application for power beaming is similar to telescopes; in fact, in our application we will use a telescope in the reverse direction. Through information gathered by the targeting laser in our application, the power transmitting laser or primary high-power laser can be fed through an active/adaptive optic system of a telescope to provide the greatest amount of resolution maintaining beam coherence at a distant target by compensating almost instantaneously for distortion and absorption affects due to scintillation in the atmosphere.

For our power beaming application, we will need to use an optical telescope similar to that used by astronomers to project our beam from the surface of the earth into the heavens. This is just opposite what telescopes were traditionally designed to do, but the theory works just as well in reversed.

For the purposes of power beaming a spot beam focused with optics alone into space meeting atmospheric turbulence and diffraction effects would expand to a 135 m beam at the GEO altitude of 35786 km. The effects of this turbulence can be reduced by operating the power beam from the highest possible place to limit the amount of atmosphere that would have to be traversed. With active optics like those on the 1.2-meter telescope at AMOS in Maui, the spot beam spreading can be reduced to about 13 meters at this altitude. Still this is a larger than we would like our beam to be spread. An application of a more advance resolution system has the answer to our beam-forming problem. Before we explore the incredibly complex world of adaptive optics, there are some parts of the telescope that we will need to understand.

First, what is the need is to understand the problem. Since the dawn of early mirrors that were nothing more than shiny metal surfaces reflective quality has been the limiting factor to image collection. With the advent of glass formed from the superheating and rapid cooling of silica, ordinary sand, those polished surfaces could be made truer and more reflective. Optics, beyond mere reflectors, were developed to focus light creating the telescope. For over 400 years, the long-standing goal of astronomers had been to increase the resolution of their telescopes. The two parameters important to visual acuity are light collecting power or diameter and angular resolution or image sharpness. To increase the collection of light, the main reflecting mirrors have gotten

larger along with the quality of the optics getting better. This allows the detection of fainter and more distant objects. In addition, the man has been taken out of the loop in favor of computer controls and digital enhancement.

> For a perfect telescope used in a vacuum, resolution is directly proportional to the inverse of the telescope diameter. A plane wavefront from distant star (effectively at infinity) would be converted by the telescope into a perfectly spherical wavefront, forming the image, with an angular resolution only limited by light diffraction - aptly called the diffraction limit.[22]

C. PASSIVE OPTICS

Here we look at the type of telescope that you might have in the backyard. With it, you could view the inner planets out to about Jupiter. You would need a larger, heavier, more permanently mounted mirror to see much past that. The logistics of that need will require the astronomer to seek a more stable structure and a firmer foundation. The astronomer will also now be concerned about the atmospheric envelope of his telescope. He will want to control the environmental conditions as much as possible. In the past astronomers have climbed to higher, drier, and colder altitudes.

> Until recently, the astronomical telescope has remained a "passive" instrument. Without any in-built corrective devices to improve the quality of star images during observations, the only possible adjustments were those performed during daytime or at the beginning of the night.[23]

> Although it was thought that atmospheric distortions could not be avoided, mechanical improvements have been made to minimize telescope errors. Mirror figuring and polishing were improved, and stiffer structures and mirrors used to minimize gravitationally induced deformations. Low-expansion glass was introduced to avoid mirror distortions as temperature varies. To reduce local temperature effects, heat dissipation from motors and electronic equipment was minimized during the night, and the dome, which in addition shields the telescope from the effects of wind buffeting, cooled during the day. In such properly designed and well-manufactured medium size telescopes, image quality is limited mainly by atmospheric distortions.

[22] Monnet, G., European Southern Observatory, "An Introduction in to Active and Adaptive Optics," 21 September 2000, <http://www.eso.org/projects/aot/introduction.html>, (Sept 2005).

[23] Monnet, G., European Southern Observatory, "An Introduction in to Active and Adaptive Optics," 21 September 2000, <http://www.eso.org/projects/aot/introduction.html>, (Sept 2005).

The science of optics alone had about reached its zenith in its ability to provide near perfect mirrors and incredibly precise alignments. Other advances would have to be wrought to compensate for the perturbations encountered when looking through even the thinnest of atmospheres. The science would have to look at the light waves themselves and understand the way it was being distorted.

> Both atmospheric and telescope errors distort the spherical wavefront, creating phase errors in the image-forming ray paths, as depicted in Figure 20Even at the best sites, ground-based telescopes observing at visible wavelengths cannot, because of atmospheric turbulence alone, achieve an angular resolution better than telescopes of 10- to 20-cm diameter. For a 4-m telescope, atmospheric distortion degrades the spatial resolution by more than one order of magnitude compared with the diffraction limit, and the intensity at the center of the star image is lowered by a factor of 100 or more. The cause is random spatial and temporal wavefront perturbations induced by turbulence in various layers of the atmosphere; one of the principal reasons for flying the Hubble Space Telescope was to avoid this image smearing. In addition, image quality is affected by permanent manufacturing errors and by long time scale wavefront aberrations introduced by mechanical, thermal, and optical effects in the telescope, such as defocusing, de-centering, or mirror deformations generated by their supporting devices.[24]

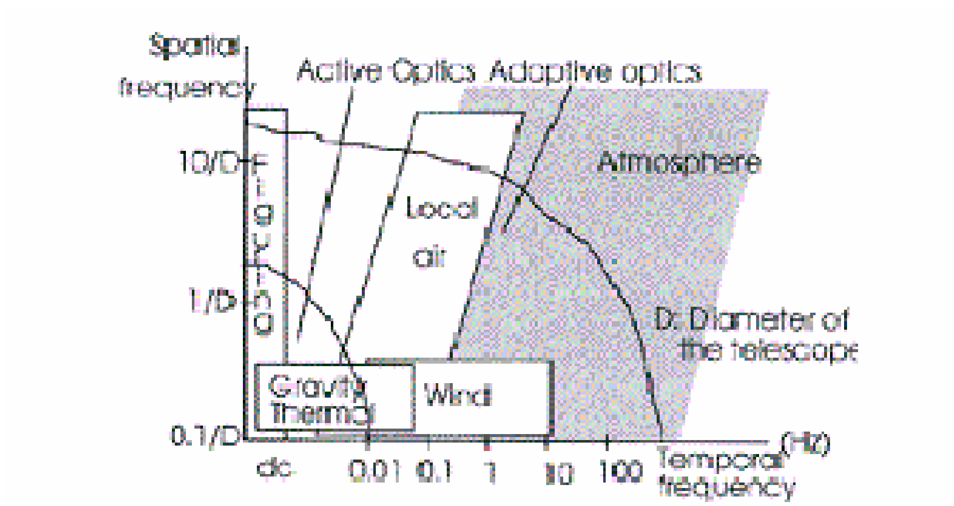

Figure 20 Spatial Frequency vs. Temporal Frequency

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[24] Monnet, G., European Southern Observatory, "An Introduction in to Active and Adaptive Optics," 21 September 2000, <http://www.eso.org/projects/aot/introduction.html>, (Sep 2005).

Spatial frequency is a characteristic of any structure that is periodic across position in space. The spatial frequency is a measure of how often the structure repeats per unit of distance. In optics, it is measured in lines per millimeter. *Temporal frequency* is a little more nebulous. It is measured in Hertz. Temporal or time in this application is not constant and exhibits a cyclic nature that can be quantized. Temporal frequency would best be defined as a characteristic of any structure that would be seen as periodic across a given length of time. In this instance, it is the front of a time wave that appears to brighten and darken with its cyclic change in frequency. Temporal frequency is closely linked to Spatial frequency and is often referenced in conjunction with the latter. Astronomers, continuously on the lookout for ways to increase their image quality have looked to active and adaptive optics to increase the image quality to the diffraction limits of their main mirrors.

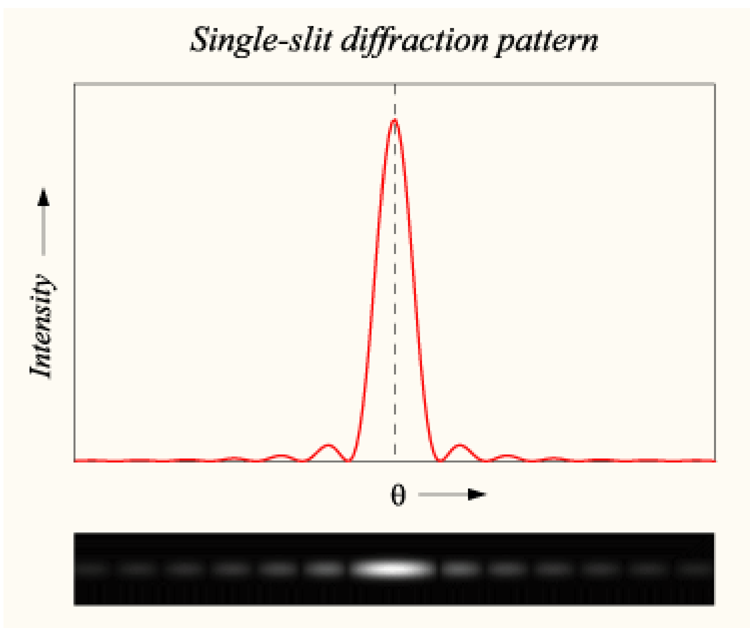

Figure 21 Diffraction limit

D. ACTIVE OPTICS

The major concern with larger mirrors is the weight of the main mirror. The structure to support the mirror traditionally would also keep the mirror from deforming. This is a much greater problem as the mirror increases in size and collaterally in thickness. A working limit is quickly reached constraining the size of optical telescopes.

The recent advent of active optics uses thinner mirror and active controls to reshape the main mirror to make adjustment for correction of distortion. The weight of the main mirrors used in active optics systems is greatly reduced along with the structural requirements to support the added weight. The structures themselves are now instrumented and mechanized to be able to hydraulically, and even in some cases, electrically deform. The Keck II primary mirror is made up of thinner composite cells, Figure 22

> Ground-based Optical/Near-Infrared large Telescopes are crucial tools for the understanding of our Universe, but their image quality is severely limited by the (quasi-static) errors in the telescope itself and the (very dynamic) atmospheric turbulence inside and over the telescope. Active Optics is used to overcome the first limitation and Adaptive Optics the latter, giving ultimately images near the diffraction limit of the primary mirror. There are a number of physical limitations to adaptive optics performance, leading to successive generations of more and more techniques that are sophisticated detailed below.[25]

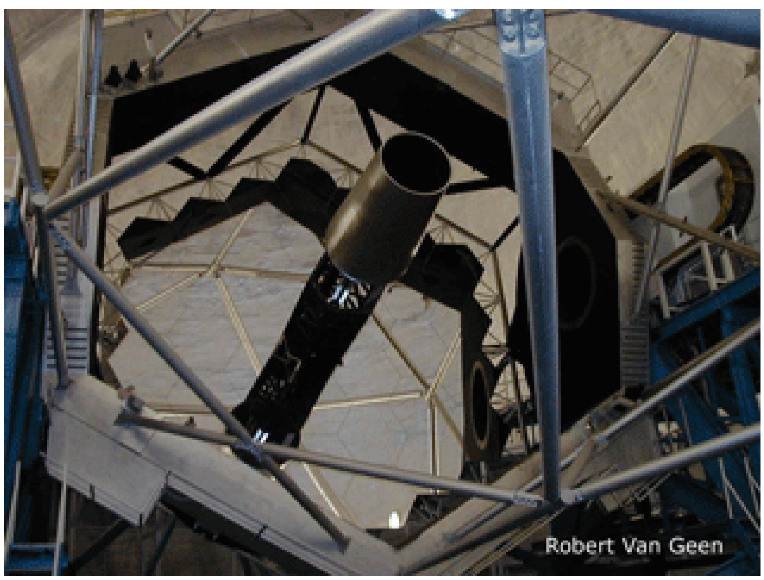

Figure 22 Keck Primary mirror

The purpose of a telescope is to look into the heavens and make observations and measurements of heavenly bodies. This usually takes large amounts of time. As the earth is continuously moving, the need to follow the track of the object precisely requires

[25] Monnet, G., European Southern Observatory, "An Introduction in to Active and Adaptive Optics," 21 September 2000, <http://www.eso.org/projects/aot/introduction.html>, (Sep 2005).

that the telescope pan. The movement of this great mass introduces deformation to the supporting structure and the mirrors that is detrimental to the observations that are being made or measured. With active controls, compensation for these subtle movements reduces the slight deformations of the telescope. The use of active, computer-controlled correction of the primary mirror allows these scientific observations to be possible.

With technological advancement continuing, new larger ground based telescopes will soon be constructed that will take advantage of this technology giving the ground based observer the best terrestrial images possible.

> As plans were developed in the 80s to enhance light-collecting power by building telescopes with primary mirrors well above 4 m in diameter, it became clear that conventional methods of maintaining image quality were ruled out by cost and structure weight limitations. As a result, the new technique of Active Optics has been developed for medium or large telescopes, with Image quality optimized automatically by means of constant adjustments by in-built corrective optical elements operating at fairly low temporal frequency ~ 0.05 Hz or less. The first fully active telescope, the ESO 3.5 m New Technology Telescope (NTT), entered into operation at La Silla in 1989. Active optics is very much at the heart of the segmented 10-m Keck primary mirror, in operation since 1992 on Mauna Kea, Hawaii and of e.g. the VLT four 8.2 m thin mirrors, now all operating in Paranal.[26]

See Chapter IV on telescopes for telescopes including: La Silla, Keck, VLT and Cerro Paranal talked about in this section. As we continue to explore the collective works of researchers in the area of active optics, we will reference part of the collection in the on-line source for information called Wikipedia.

Wikipedia defines active optics as dynamic reflective surfaces that are mechanically adjustable through the use of hydraulic systems. Figure 23 depicts the principle of Active Optics. The following excerpt is a good description on one type of active optical system.[27]

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26 Monnet, G., European Southern Observatory, “An Introduction in to Active and Adaptive Optics,” 21 September 2000, <http://www.eso.org/projects/aot/introduction.html>, (September 2005).

27 Oliver Lineham, Wikipedia, “ Active Optics,” 4 October 2005, <http://en.wikipedia.org/wiki/Active_optics>, (November 2005).

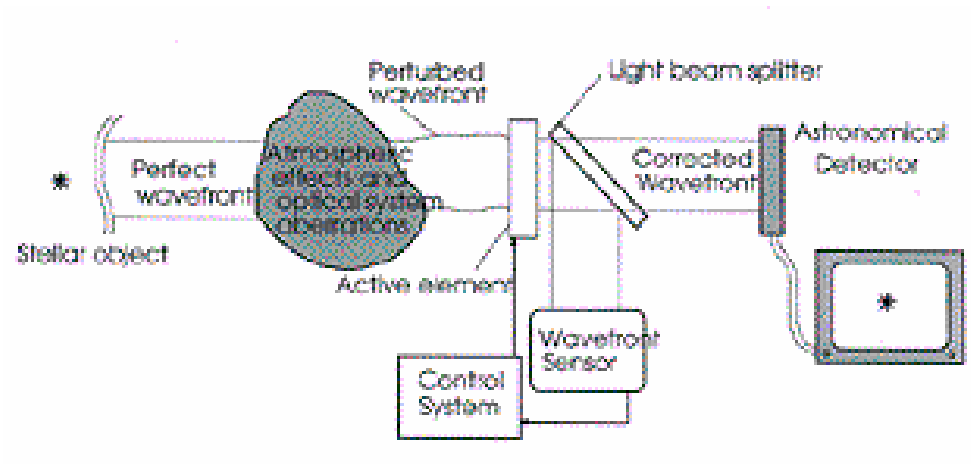

Figure 23 The principle of Active Optics

Active optics is a relatively new technology for reflecting telescopes. Active optics works by "actively" adjusting the telescope's mirrors. This method is used by, among others, the Nordic Optical Telescope, the New Technology Telescope and the Keck telescopes, as well as all large telescopes built in the last decade.

Most modern telescopes are reflectors, with the primary element being a very large mirror. Historically, a fixed weight-to-diameter relation was used to build these mirrors, limiting their maximum diameter to 5 or 6 meters (200 or 230 inches), like in the Palomar Observatory.

A new generation of telescopes uses instead very thin mirrors, which are too thin to keep themselves rigidly in the correct shape. Instead, an array of actuators behind the mirror keeps it in an optimal shape.

The combination of actuators, a quality-of-image detector, and a real-time computer program to move the actuators to obtain the best possible image is termed "active optics."

The "activeness" in their name means that the system keeps the primary mirror in its optimal shape against all environmental factors such as gravity (at different telescope inclinations), wind, telescope axis deformation, etc. Active optics correct all factors that may affect image quality at timescales of one second or more.

1. The VLT Active Optics System

The Very Large Telescope (VLT) is an example of a telescope with main mirror deformation capabilities for correcting a telescopes focal length. The VLT in Paranal, Chile is a great example of such a telescope in use today. For more information on this example refer to Appendix B and Appendix D.

E. ADAPTIVE OPTICS

The final correction of the telescope with today's technology is an attempt to reach the theoretical Diffraction limit. With adaptive optics, astronomers attempt to compensate for atmospheric/environmental turbulence. Adaptive optics sense and compensate for the atmospheric distortions of incoming light up to 670 times each second. The result of all these adjustments is an improvement in image quality on fairly bright astronomical targets of 10 to 20 times what would be seen without this capability.

All light waves spread as they propagate. This will be discussed later in the chapter on EM radiation, called the inverse square law of propagation. If light waves come into close proximity to a body, they also have the possibility of experiencing diffraction and spread further reducing their combined energy. Spatial and Temporal frequency are both affected. A final theoretical limit is reached at which a single photon cannot loose any more energy, but is required to seek a lower state. This is the point that is defined as the theoretical diffraction limit. Long before this point is reached our ability to detect those photons has elapsed. With the use of adaptive technology, the optical envelope can be further expanded to bring us closer to the diffraction limit.

The Center for Adaptive Optics defines adaptive optics as optical systems that adapt to compensate for optical effects introduced by the medium between the object and its image.[28]

> Under ideal circumstances, the resolution of an optical system is limited by the diffraction of light waves. This so-called "diffraction limit" is generally described by the following angle (in radians) calculated using the light's wavelength and optical system's pupil diameter:[29]

$$\alpha = 1.22\frac{\lambda}{D}$$

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28 Claire Max, "What is Adaptive Optics," 30 November 2004, <http://cfao.ucolick.org/ao/>, (March 2006).

29 Wikipedia, "Diffraction Limits," 2 April 2006, <http://en.wikipedia.org/wiki/Diffraction_limit>, (April 2006)

> where the angle is given in radians. Thus, the fully-dilated human eye should be able to separate objects as close as 0.3 arcmin in visible light, and the Keck Telescope (10-m) should be able to resolve objects as close as 0.013 arcsec.[30]
>
> In practice, these limits are never achieved. Due to imperfections in the cornea and lens of the eye, the practical limit to resolution only about 1 arcmin. To turn the problem around, scientists wishing to study the retina of the eye can only see details about 5 microns in size. In astronomy, the turbulent atmosphere blurs images to a size of 0.5 to 1 arcsec even at the best sites.

Iris AO, Incorporated says that, Adaptive Optics (AO) refers to optical systems that adapt to compensate for optical effects introduced by the medium between an object and its image. The diagram in Figure 24is provided by the privately funded, Iris AO Corporation. It is a description of their company's current implementation of an adaptive optics system. Iris elevates their micro-mirrors using three different approaches. The Electromagnetic approach uses solenoidal structures. The Electrostatic approach uses vertical comb-drives. The third actuation system uses a thermal bio-morphed structure to provide thermal actuation and was the company's initial research approach. Figure 24 shows a micron level view of what is actually happening to the optical surface. Further explanation is included in Appendix 0.

> Astronomers have used AO in recent years to remove atmospheric interference from images enabling a level of clarity from ground telescopes rivaling that provided by the Hubble Space Telescope. This technology holds great promise for other fields, such as vision science, which encounter similar effects due to high order spatial aberrations and additional temporal changes.[31]
>
> AO provides a means of compensating for the effects of atmospheric distortion, leading to appreciably sharper images sometimes approaching the theoretical diffraction limit. With sharper images comes an additional gain in contrast -- for astronomy, where light levels are often very low, this means fainter objects can be detected and studied.

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30 Claire Max, "What is Adaptive Optics," 30 November 2004, <http://cfao.ucolick.org/ao/>, (March 2006).

31 Iris AO Inc., "A Revolution in Adaptive Optics," 15 October2004, <http://www.irisao.com/technology.html>, (November 2005).

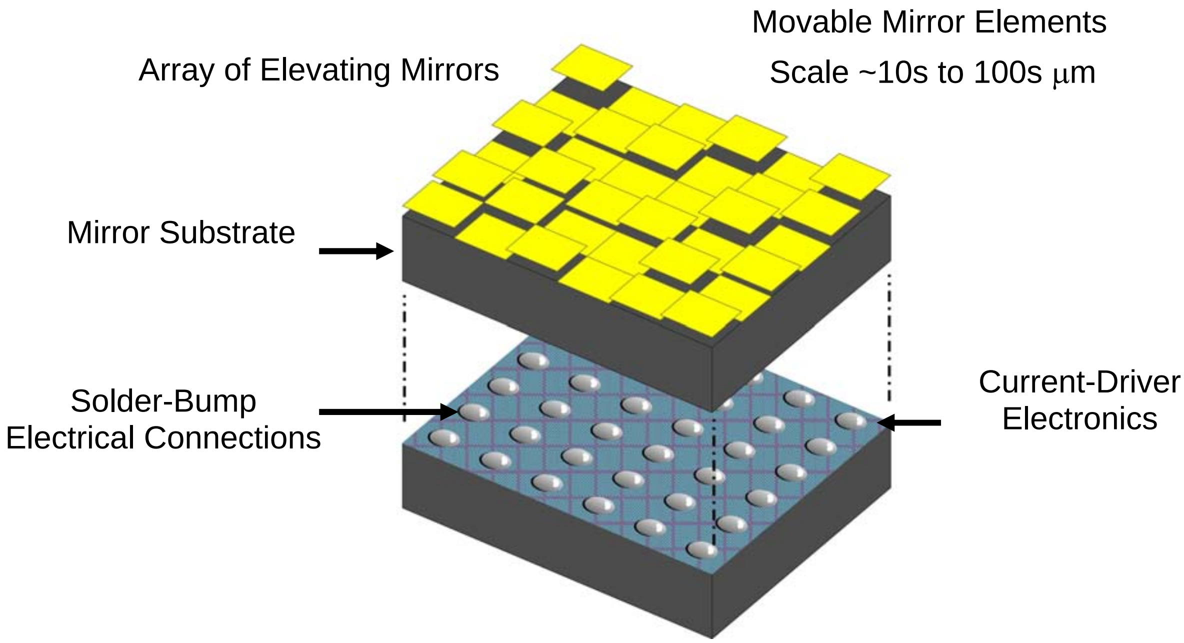

Figure 24 Adaptable-Mirror Section[32]

1. Adaptive Optics Packages

In the world today there are multiple adaptive optics systems working on various telescopes with primary mirrors in the neighborhood of 13 feet (4 meters) or greater. The following discussion will talk about some of the systems being employed on the new generation of modern telescopes. Figure 25 shows the increased resolution when applying adaptive optics. By measuring the distortion and compensating this type of image quality is possible.

32 Michael A. Helmbrecht, Ph.D., "Iris AO History," 15 October 2004, <http://www.irisao.com/about_us.html>, (November 2005).

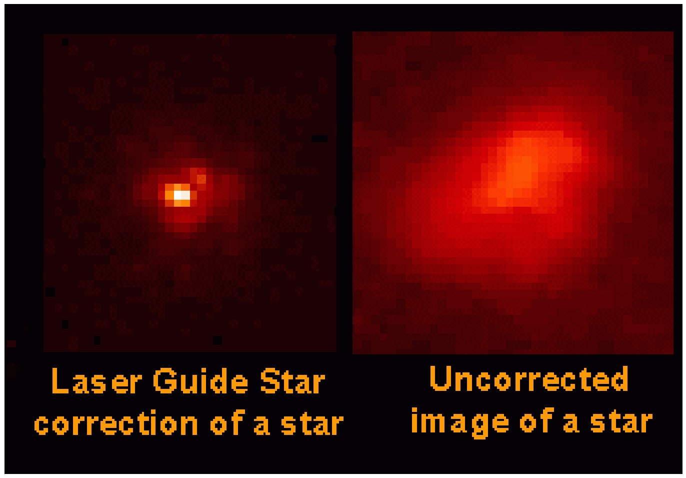

Figure 25 A Before and After Picture of AO correction

a. ADONIS

ADONIS (**Ad**aptive **O**ptics **N**ear **I**nfrared **S**ystem) is an Adaptive Optics system available to the astronomical community since April 1993. ADONIS is installed and operated by specialized European Southern Observatory (ESO) Staff at their 3.6 m telescope on La Silla (the Saddle) Mountains in Chile and can be used by astronomers without any knowledge of adaptive optics. The reference wavefront is sensed in the visible spectrum. The observation is done in the near-infrared (1-5µm) with one of two proposed imaging cameras dedicated to this instrument.

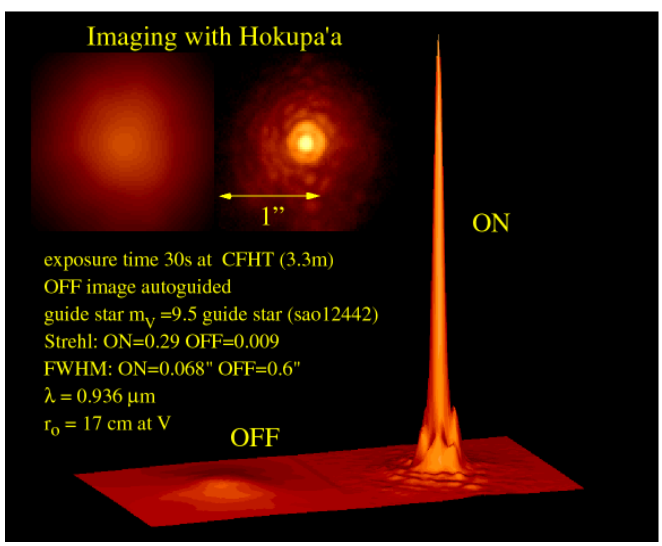

Figure 26 3-D plot of the intensity distribution in a stellar image.

b. *ADOPT*

The Adaptive Optics module of Telescopio Nazionale Galileo (AdOpt@TNG) is permanently mounted at the ***Nasmyth A*** interface and provides two distinct kinds of correction: the tip-tilt (T/T) and high orders (HO) corrections. Both kinds of corrections have already been implemented at first light. At the moment only the T/T compensation is available for observations while the HO correction needs to be further optimized and its availability is foreseen during 2001.[33]

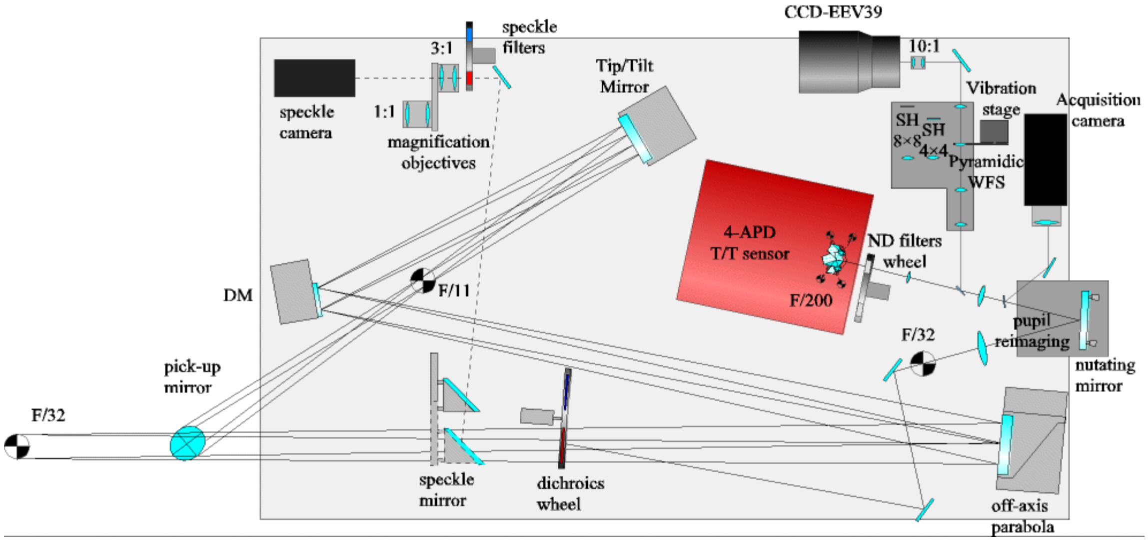

Figure 27 Scheme of the Adaptive Optics Module (AdOpT)

c. *ALFA*

ALFA: Mounted on the Calar Alto 3.5-meter telescope was the first to routinely use a laser guide star projector.

> The Arecibo L-band Feed Array (ALFA) is a seven feed system that will allow large-scale surveys of the sky to be conducted with unprecedented sensitivity using the 305-m Arecibo telescope in Puerto Rico. The NAIC Arecibo Observatory telescope, operated by Cornell University for the National Science Foundation, is the largest and most sensitive single dish radio telescope in the world and is used to study large numbers of sources that are too faint to be seen with other telescopes. In the past, use of the telescope as a survey instrument has been limited by the relatively small field of view in a single observation. ALFA, operating near 1.4 GHz, will

33 Massimo Cecconi, "Adaptive Optics Module," <http://www.tng.iac.es/instruments/adopt/> (May 2006).

consist of a cluster of seven cooled dual-polarization feeds, a fiber-optical transmission system, and digital back-end signal processors. The system will enable deep surveys for a variety of objects in the Milky Way Galaxy and of other galaxies for probing cosmology. As such, the multibeam system will have a broad appeal to astronomers from all over the world.[34]

d. ChAOS

The Chicago Adaptive Optics System (ChAOS) on the 3.5-m ARC telescope at Apache Point, New Mexico. Figure 28shows the AO system mounted to the telescope. Figure 26shows the resolution increase observed. Close loop means the AO system was active.

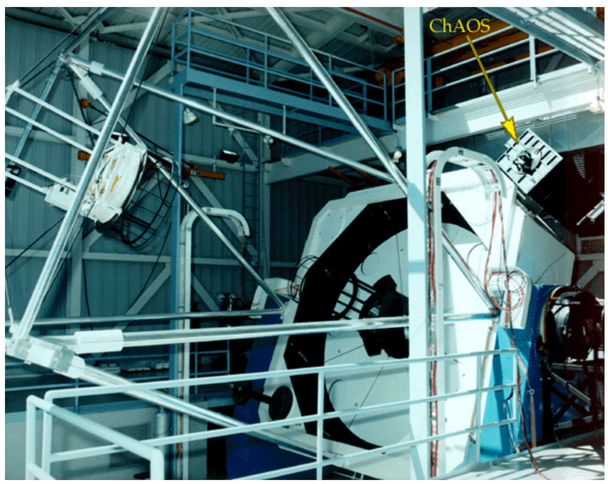

Figure 28 ChAOS mounted on Apache Point 3.5m Telescope

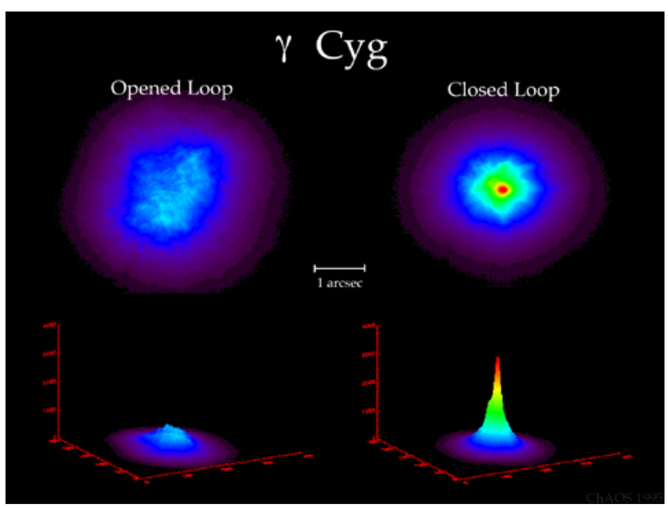

Figure 29 Graphical Resolution increase Observed

34 Bob Brown, "Arecibo L-Band Feed Array," 27 Janruary 2005, <http://alfa.naic.edu/>, (June 2005).

e. *Hokupa'a*

Hokupa'a is a natural guide star (NGS), curvature-sensing adaptive optics system (AOS) built by the University of Hawaii. It gives near diffraction-limited resolutions in the K and H bands. Hokupa'a is based around a 36-element curvature wavefront sensor (WFS) and bimorph mirror. In brief, Hokupa'a makes wavefront measurements using pairs of extra-focal images whose differences are proportional to the curvature of the wavefront. A lenslet array and a set of avalanche photo-diodes (APDs) define the sub-elements in the measurement. A deformable mirror (DM) with an arrangement of actuators matched to the wavefront sensor is shaped into a conjugate of the measured aberrations to correct the wavefront. The corrected light with wavelength shortward of 1µm is sent to the WFS while light longward of 1µm is sent to the science instrument, Figure 30[35]

Figure 30 Hokupa'a mounted on the Gemini North Telescope.

f. *LLNL AO system*

The LLNL AO system feeds an AO-optimized IR camera known as IRCAL. IRCAL uses a 256x256 Rockwell Planetary Integrated Camera Near-Infra-red Camera (PICNIC) array (similar to a NICMOS-3 detector) which is sensitive from 0.9 - 2.5 microns and provides Nyquist sampled imaging at 2.2 microns (0.075 arc seconds per pixel). PICNIC is a 256x256 Short wave Infrared (SWIR) hybrid with a four independent quadrant outputs. The internal image quality is excellent over the entire 19.4

[35] Phil Puxley, "Hokupa'a Introduction," 23 Janruary 2002, <http://www.gemini.edu/sciops/instruments/uhaos/uhaosIndex.html,> (April 2006).

arc second field of view. IRCAL is equipped with standard near-IR photometric filters; some 1% filters are also available.[36] LLNL AO system is mounted at the 3.5-m Shane telescope of the Lick Observatory.

g. NAOS[37]

NAOS (Nasmyth Adaptive Optics System) is also the Greek name for, 'the ship' or 'temple'. NAOS is actually the inner portion of a Greek temple, enclosed within walls and generally surrounded by colonnaded porticoes. In it stood the statue of the deity to whom the temple was consecrated. Funnily enough, this is also the name of the great ship that carried the Argonauts. Probably more related to the name of an adaptive optics system to a very good telescope is the fact that is also the name of a very large star. The constellation Argo was found to be so large in the 19th century that it was broken into parts; Carina, 'the keel,' Vela, 'the sails', and Puppis, 'the stern.' Naos, the Zeta star of Argo, was part of Puppis and became known as Zeta Puppis. Stranger still, this dieing star mere astronomical years from going supernova is also bearing the connotation of being 'connected to death by drowning.'[38] The adaptive optics system, NAOS, is equipped with both visible and infrared wavefront sensors.

h. PUEO

PUEO is an adaptive optics system built for the Canada-France-Hawaii Telescope (CFHT). PUEO is named after the sharp-eyed Hawaiian owl, see Figure 31, because it helps to sharpen the vision of the telescope. It is also an acronym and stands for Probing the Universe with Enhanced Optics. Image distortion caused by atmospheric turbulence is measured by highly sensitive light detectors and corrected by a precisely controlled flexible mirror. CFHT is a non-profit organization that operates a world-class 3.6-meter telescope atop Mauna Kea.

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36 Center for Adaptive Optics, "Lick AO System Information," 14 March 2000, <http://mthamilton.ucolick.org/techdocs/instruments/AO/index.html>, (April 2006).

37 Paranal Science Operations Team, "NAOS - Nasmyth Adaptive Optics System," 22 February 2006, <http://www.eso.org/instruments/naos/>, (April 2006).

38 Vivian E. Robson, "The Fixed Stars and Constellations in Astrology," 1923, Ascella Publications, UK, ISBN: 1 898503 50 8.

Figure 31   A Hawaiian Pueo Owl

i. PUEO NUI

A high dynamic range and visible AO upgrade for PUEO.

j. SINFONI[39]

SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared) is a near-infrared (1 - 2.5 μm) integral field spectrograph fed by an adaptive optics module, currently installed at the Cassegrain focus of UT4 at the PARANAL OBSERVATORY (Chile), see Figure 32

Figure 32   The SINFONI Adaptive Optics Package[40]

[39] Paranal Science Operations Team, European Southern Observatory, “SINFONI,” 26 February 2006, <http://www.eso.org/instruments/sinfoni/>, (April 2006).

F. SUMMARY

This chapter looked at the concepts of the passive, active and adaptive optics. In addition, both active and adaptive systems are further discussed in the appendixes (SHOULD BE Appendices) for the advanced researcher. We covered several examples of systems available.

In the next chapter, we will look at some of the telescopes with large main mirror systems that are fitted with active and adaptive optics that could be potentially used to provide the capability of power beaming. Particularly important to our research is the AMOS facilities in Hawaii.

40 Paranal Science Operations Team, European Southern Observatory, "SINFONI," 26 February 2006, <http://www.eso.org/instruments/sinfoni/>, (April 2006).

V. TELESCOPES

A. CHAPTER OVERVIEW

This chapter explores telescopes greater than 3.5 meters with adaptive optical packages. This is important to power beaming to prevent beam scattering and compensate for atmospheric anomalies allowing projection near the diffraction limit.

B. AMOS

The Air Force Maui Optical Station (AMOS) is located at the summit of Haleakala, on the island of Maui. It is part of the Maui Space Surveillance Site (MSSS), see Figure 33. This facility has the optimum opportunity to assist in experimentation leading up to developing a ground based power-beaming infrastructure. AMOS is the only truly all military asset that is dedicated to the process of development. In the past AMOS has partnered with NPS to conduct ranging experiments on the PANSAT 1, a NPS satellite experiment.

Figure 33 AMOS, part of the Maui Space Surveillance System

> The **Maui Space Surveillance System (MSSS)** is a state-of-the-art electro-optical facility combining operational satellite tracking facilities with a research and development facility, the only one of its kind in the world. The MSSS houses the largest telescope in the Department of

Defense, the 3.67-meter Advanced Electro Optical System (AEOS), as well as several other telescopes ranging from 0.4 to 1.6 meters.[41]

The 3.67-meter telescope, known as the Advanced Electro-Optical System (AEOS), owned by the Department of Defense, is the nation's largest optical telescope designed for tracking satellites. The 75-ton AEOS telescope points and tracks very accurately, yet is fast enough to track both low-Earth satellites and missiles. AEOS can be used simultaneously by many groups or institutions because its light can be channeled through a series of mirrors to seven independent coudé rooms below the telescope. Employing sophisticated sensors that include an adaptive optics system, radiometer, spectrograph, and long-wave infrared imager, the telescope tracks man-made objects in deep space and performs space object identification data collection.

AEOS is equipped with an adaptive optics system, the heart of which is a 941-actuator deformable mirror that can change its shape to remove the atmosphere's distorting effects. Scientists are expected to get near diffraction-limited images of space objects.[42]

The mission of AMOS is to conduct research and development of new and evolving electro-optical sensors, as well as to provide support for operational missions defined by US and AF Space Command. In addition, AMOS provides experiment support to a wide variety of military and civilian organizations in diverse fields. This support has included the Strategic Defense Initiative Organization (SDIO), the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), and many universities. AMOS has hosted and supported a wide variety of visiting experiments.[43]

C. GEMINI-NORTH TELESCOPE

Gemini is an international partnership managed by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation.[44]

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41 Air Force Research Laboratory Detachment 15, "Maui Space Surveillance System," <http://www.maui.afmc.af.mil/>, (May 2006).

42 Air Force Research Laboratory Detachment 15, "Air Force Research Lab (AFRL)," <http://www.maui.afmc.af.mil/about.html>, (May 2006).

43 Charles P. Vick, Sara D. Berman, and Christina Lindborg, "Air Force Maui Optical Station (AMOS)," 26 February 2003, <http://www.fas.org/spp/military/program/track/amos.htm>, (May 2006).

44 Doug Welch, "Gemini Observatory," <http://www.gemini.edu>, (April 2006).

The Gemini Observatory is an international partnership involving the United States, the United Kingdom, Canada, Australia, Chile, Brazil, and Argentina. The partnership has constructed and now operates two 8-meter telescopes: one in the Northern Hemisphere on Mauna Kea, HI, and one in the Southern Hemisphere on Cerro Pachon, Chile. The twin telescopes are infrared-optimized, have superb image quality, and provide unprecedented optical and infrared coverage of the northern and southern skies for astronomical research. Scientific operations began on Gemini North in 2000 and on Gemini South in summer 2001.[45]

The Gemini Observatory consists of twin 8-meter optical/infrared telescopes located on two of the best sites on our planet for observing the universe. Together these telescopes can access the entire sky, see Figure 34.[46]

The Frederick C. Gillett Gemini North Telescope is located on Hawaii's Mauna Kea as part of the international community of observatories that have been built to take advantage of the superb atmospheric conditions on this long dormant volcano that rises almost 14,000 foot into the dry, stable air of the Pacific. The Gemini Observatory's international headquarters is located in Hilo, Hawaii at the University of Hawaii at Hilo's University Park.

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45 National Science Foundation, "Progam Budgets," <http://www.nsf.gov/funding/pgm_summ.jsp>, (May 2006)

46 Doug Welch, "Gemini Observatory," <http://www.gemini.edu>, (April 2006).

Figure 34 Diagram of Gemini Telescope Structure

D. GEMINI-SOUTH TELESCOPE

The Gemini South telescope is located at almost 9,000-foot elevation on a mountain in the Chilean Andes called Cerro Pachón. Cerro Pachón shares resources with the adjacent SOAR Telescope and the nearby telescopes of the Cerro Tololo Inter-American Observatory.

Both of the Gemini telescopes have been designed to take advantage of the latest technology and thermal controls to excel in a wide variety of optical and infrared capabilities. One example of this is the unique Gemini coating chamber that uses "sputtering" technology to apply protected silver coatings on the Gemini mirrors to provide unprecedented infrared performance.

Gemini's aggressive instrument program keeps the observatory at the cutting edge of astronomical research. By incorporating technologies such as laser guide stars, Multi-Conjugate Adaptive Optics and multi-object spectroscopy, astronomers in the Gemini partnership have access to the latest tools for exploring the universe.

E. PARANAL OBSERVATORY

The Paranal Observatory is located on the top of Cerro Paranal in the Atacama Desert in the northern part of Chile and what is believed to be the driest area on Earth. Cerro Paranal is an 8645-ft (2,635-m) high mountain, about 75 miles (120 km) south of the town of Antofagasta and 7.5 miles (12 km) inland from the Pacific Coast. The geographical coordinates are 24^{o} 40' S, 70^{o} 25' W.[47]

The Paranal Mountain was chosen because of its excellent atmospheric conditions and, not the least, its remoteness. This will ensure that the front-line astronomical observations to be carried out there will not be disturbed by adverse human activities, e.g. dust and light from roads and mines.

The sky is photometric in 78 % of the nighttime with the 50 % fractile 0.66" full width at half maximum (FWHM).

Figure 35 Paranal Observatory Complex, Cerro Paranal, Chile

F. SOAR

The SOAR (Southern Observatory for Astrophysical Research) Telescope is a 4.1 m diameter altitude-azimuth optical telescope constructed by a consortium of the

47 Paranal Observatory, "About Cerro Paranal," 8 December 2004, <http://www.eso.org/paranal/site/paranal.html>, (March 2006)

Brazilian Ministry of Science, the National Optical Observatories, the University of North Carolina and Michigan State University.[48]

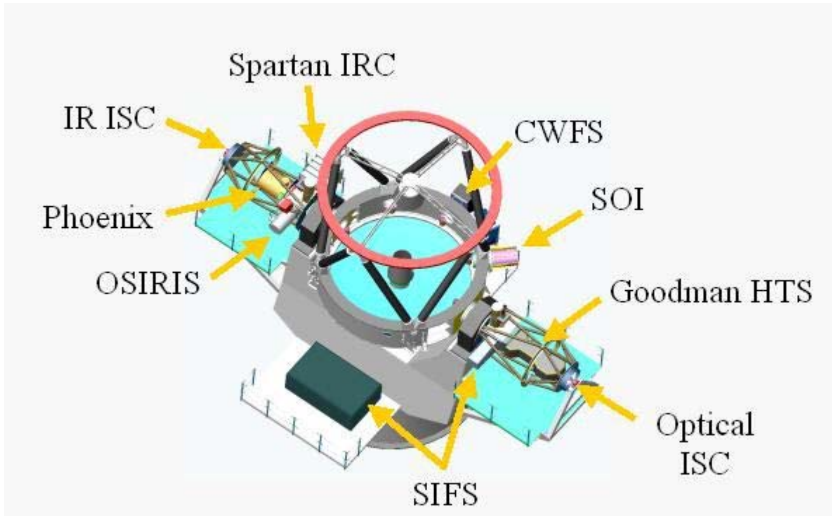

Figure 36 SOAR Telescope

It is located at Cerro Pachon, in Chile, and was designed to work from the atmospheric cut-off in the blue (320 nm) to the near infrared, to have excellent image quality (0.22 arc seconds), fast slewing and to have up to nine instruments mounted ready for use.

Its primary mirror is only 10 cm thick and is supported by 120 electro-mechanical actuators, to set and hold its optimum shape. The tertiary mirror will partially correct the atmospheric turbulence by tip-tilting at 50 Hz.

The SOAR Telescope is designed to carry a large instrument payload. An Instrument Support Box (ISB) at each Nasmyth focus can carry a cluster of three instruments with a total weight of up to 3000kg, and contains a shared Tip-Tilt guider and calibration unit. Two "Folded Cassegrain" ports on the elevation ring can each support an additional smaller instrument weighing up to 300kg. A third such port holds the Calibration Wavefront Sensor used to tune the Active Optical System. The system is designed to allow the observer to switch between instruments, several of which will be “science ready” at any time, within a few minutes. The tertiary mirror rotates to select the focal station in use while beam steering optics within each ISB directs the light to the chosen instrument.

48 Southern Astrophysical Research Telescope, <http://www.soartelescope.org>, (April 2006)

G. TNG (ADOPT)

The Telescopio Nazionale Galileo (TNG), with a primary mirror of 3.58m, is the national facility of the Italian astronomical community, and is located at Roque de Los Muchachos Observatory (ORM).[49]

It was operated by the Centro Galileo Galilei (CGG) that was created in 1997 by the Consorzio Nazionale per l'Astronomia e l'Astrofisica (CNAA). In 2002, it became a part of the Italian National Institute of Astrophysics (INAF) which is ensuring its financial support.

TNG is equipped with five instruments that are permanently operating on its foci and offer a large variety of observing modes covering the optical and near infrared wavelength ranges and spanning from broadband imaging to high-resolution spectroscopy.

M1 diameter	3.58m
Focal length	38.5m (f/11)
M2 diameter	0.875m
M2 baffle diameter	1.165m
Scale	5.36arcsec/mm
Vignetting-free field	25arcmin diameter

Table 3 ADOPT Parameters

The telescope is located at 17º52´34" East Longitude, 28º45´34" North Latitude at 2400 meters (7874 feet).

The main feature of the TNG is the presence of an AO system to perform real-time, low frequency correction of the optical components in order to ensure the best optical performances in all conditions and to compensate for the deformations of the primary mirror (M1), which is too thin to be completely rigid. The AO system consists of two Shack-Hartman wavefront sensors (one for each focus) to sense wavefront deformations using an off-axis star. This information, properly treated, is used to correct the optical surface of the primary mirror (M1) and the positions of the secondary and tertiary mirrors (M2 and M3). The M1 surface is modified through 78 mechanical actuators pushing axially on the M1

[49] Italian Institute on Astrophysics, “Fundación Galileo Galilei,” <http://www.tng.iac.es>, (April 2006).

back face; M2 is mounted on an hexapod system (six expandable arms) used to keep the mirror in the correct position and tilt with respect to M1; a three piezoelectric actuators system can tilt M3 around two perpendicular axis up to a frequency of 5 Hz. Measurements of the optical performances achieved during tests done at the Zeiss laboratories show that the 80% of the Encircled Energy is within 0.11" at a wavelength of 632nm.[50]

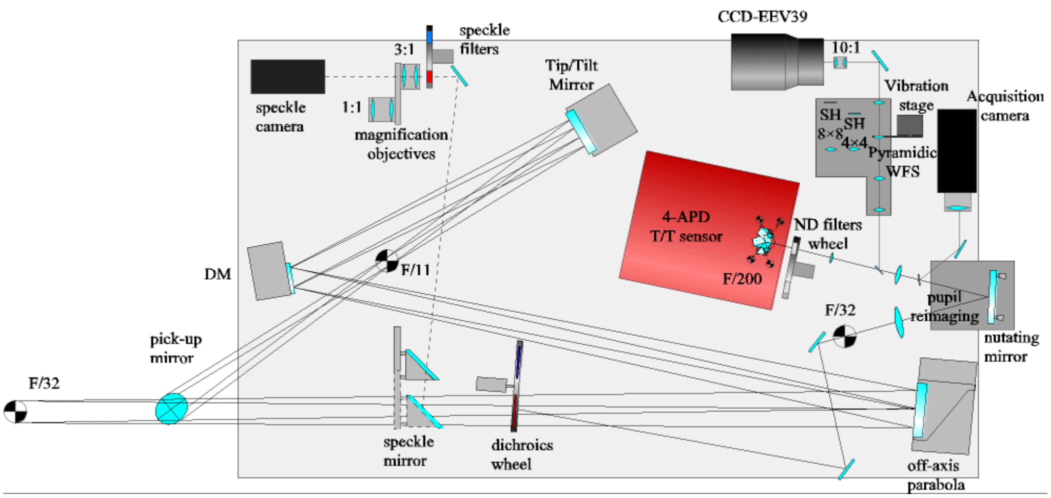

Figure 37 ADOPT Module

H. W. M. KECK OBSERVATORY

The University of Hawaii's Institute for Astronomy (IfA) manages an 11,600-acre science reserve at the summit of Mount Mauna Kea. Shared by a dozen major research facilities, representing a capital investment of more than $1 billion and employment for several hundred Big Island residents, The IfA estimates that more than 80% of the combined annual operating costs for all observatories around the world are spent in Hawaii, predominantly on the big island of Hawaii. This is employment for hundreds of Big Island residents. Amid this gathering of telescopes, the Kecks are unique. [51]

> Keck's capabilities make full use of Mauna Kea's research potential. Surrounded by thousands of miles of relatively thermally stable ocean, the 13,796-foot Mauna Kea summit has no nearby mountain ranges to roil the upper atmosphere or throw light-reflecting dust into the air. Few city lights pollute its extremely dark skies. For most of the year, the atmosphere above Mauna Kea is clear, calm and dry.

50 Italian Institute of Astrophysics, "Fundación Galileo Galilei ," <http://www.tng.iac.es >, (April 2006).

51 Keck Observatory, "About Keck," 2005, <http://www.keckobservatory.org>, (April 2006).

Figure 38 Keck Binary Telescope: World largest visual and Infrared

I. SUMMARY

In this chapter we explored some the major telescopes over 3.5 meters using adaptive optics. With future telescopes planned with main mirrors of 21.4 meters like the proposed Giant Magellan Telescope, the future for optical exploration is bright.

The following chapter describes the workings of solar cells. An understanding of these devices will help us understand how the use of lasers, optics, and telescopes to conduct power beaming into space can affect spacecraft power budgets.

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VI. SOLAR CELLS

A. CHAPTER OVERVIEW

This chapter presents background information on solar cells for the purposes of giving the reader more of an idea how power beaming will affect on-board power systems. The discussion begins with a basic review of atomic structure and expands the understanding of the reader on what semi-conducting materials are and how they work to create a flow of energy.

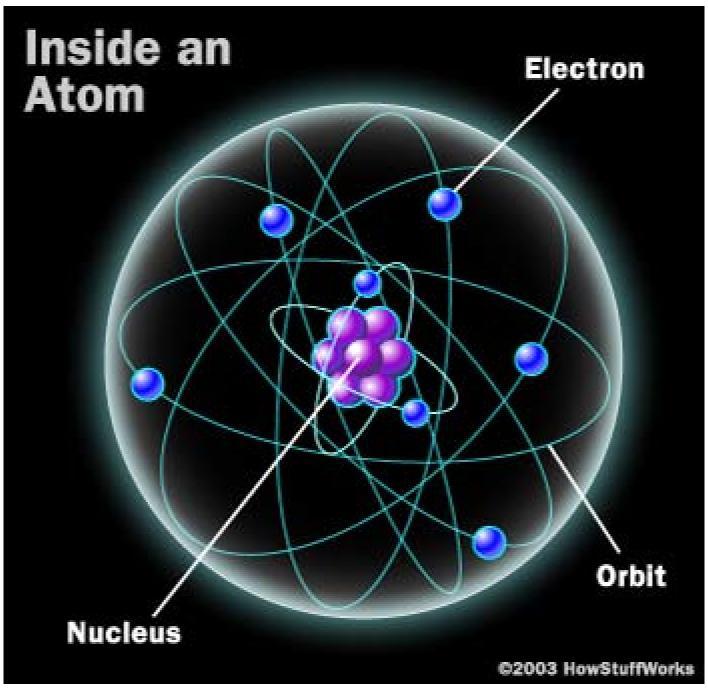

Figure 39 The Accepted Structure of an Atom[52]

B. SEMICONDUCTORS

A semiconductor is a material with a resistance to electron flow in between a conductor such as copper with a value of resistivity (ρ) equal to 10^{-6} Ω·cm and an insulator such as mica with a resistivity equal to 10^{12} Ω·cm. The semi conductor elements are carbon, silicon, germanium, tin, and lead. These intrinsic elements have

52 Matthew Weschler, "How Lasers Work," <http://science.howstuffworks.com/laser1.htm>, (May 2006).

four valence electrons and are as likely to share their valence electrons with similar elements in this column to form a stable outer shell, see Figure 40Germanium has a resistivity of 50 Ω·cm while silicon has a resistivity of 50 x 10^3 Ω·cm.

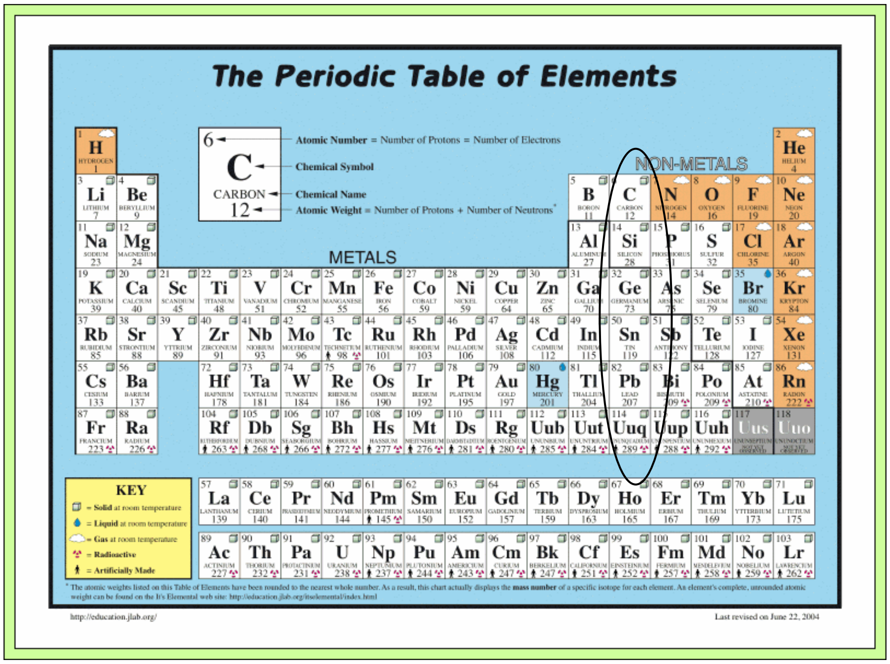

Figure 40 Periodic Table of Elements

In pure or intrinsic germanium (Ge) and silicon (Si) crystals the four valence electrons (See Figure 39) in the outer shell of each atom are covalently bonded with the four adjoining atoms, such that each atom will have a balanced eight electrons shared in their outermost shell. Figure 42shows a single lattice structure. The center atom has shared one of its four valence electrons with each of its four neighbors and borrowed one electron from each neighbor to balance its outer shell.

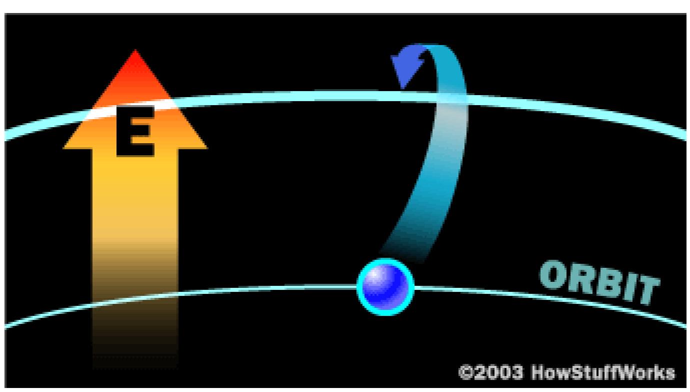

Figure 41 Electron Changing Energy States

An important term discussed often in the study of semiconductors is the concept of band gap. The band gap is the energy difference between the top of the valence band and the bottom of the conduction band. An intrinsic semiconductor's conductivity is strongly dependent on the band gap energy. The only available carriers for conduction are the electrons that have enough thermal energy to be excited across the band gap, see Figure 41 Table 4 lists semiconductors with their respective band gaps.

The conduction bands are energy levels at higher energies than the valence band of an element. They are better defined as a group of energy states that are empty at zero degrees Kelvin and are available to support the movement of electrons that gain sufficient energy to jump from the valence band to empty levels in the conduction band.[53]

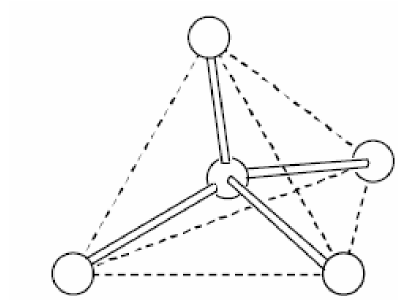

Figure 42 Germanium and Silicon Single Crystal Structure

Covalent bonding is stronger than the weakest nuclear force that binds the electron to the proton. This lattice arrangement is completely stable at zero degrees Kelvin, but as energy is absorbed in heating, the weak valence electrons tend to vibrate more and become susceptible to being freed from the lattice structure polarizing the remaining structure. If the homogeneous material looses some electrons due to excitation by photons, the material as a whole becomes polarized into a positively charged material. This movement of electrons is an effect that we can take advantage of if we use an impurity that is closely related to the base material. In the case of silicon and germanium, adding a small amount of a pnictogen impurity like nitrogen, phosphorus, arsenic, or antimony will change the overall properties of the new material. An outer valence

[53] IC Knowledge, "Glossery of Integrated Circuit Terminology," <http://www.icknowledge.com/glossary/c.html>, (May 2006).

electron will be available to be easily striped allowing the outer valence shell to balance. The presence of the weakly bound electron causes the material to be considered a material with excess electrons. This new material is said to be negatively doped. We classify this material as N-type or Negative-type material. Electrons will continue to be very loosely bound and will be easily moved by photons of .05 electron volts (eV) for silicon or .01 eV for germanium.

Si	1.14 eV
Ge	0.67 eV
InN	0.7 eV
InGaN	0.7 - 3.4eV
InP	1.34 eV
GaAs	1.43 eV
AlGaAs	1.42 - 2.16 eV
AlAs	2.16 eV
InSb	0.17 eV
SiC 6H	3.03 eV
SiC 4H	3.28 eV
GaN	3.37 eV
Diamond	5.46 - 6.4 eV

Table 4 Typical Band gap Energies for Semiconductors[54]

When silicon is dope with an element with only three valence electrons like boron, aluminum, gallinium, or indium atoms, the new material is considered positive and classified as p-type material. The same is true of the other semiconductor elements: carbon, germanium, tin, and lead.

1. The p-n Junction Under Open-Circuit Conditions

An interesting effect happens when two oppositely doped materials are placed side by as in Figure 43A p-n junction is formed. The region between the two materials gives up its inherent qualities as electron leap from the n-type material to the p-type material. A boundary is formed with negative charges attracted to the p-material and

54 Smith, V., Wikipedia, “Band gap,” 13 February 2006, <http://en.wikipedia.org/wiki/Bandgap>, (May 2006).

holes, or positive charges, attracted to the n-material. This region of the new composite material's center region that has been depleted of free electrons and holes is called the depletion region.

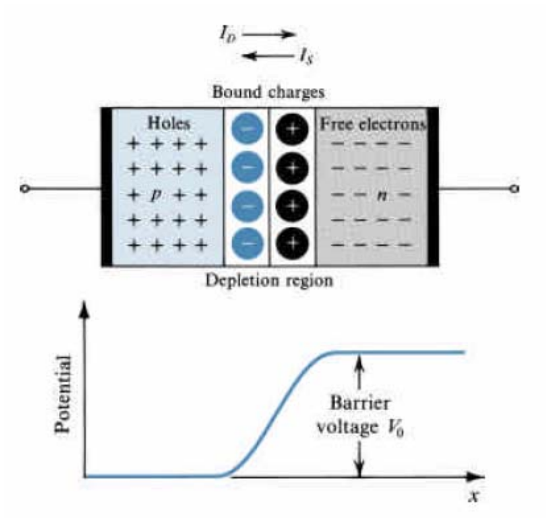

Figure 43 P-N junction and Barrier Voltage Diagram

a. Diffusion Current ID

Due to the high concentration of holes in the *p*-materials, as compared to low concentration of holes in *n*- material, the holes will migrate or diffuse from *p*-side to *n*-side causing the diffusion current I_D, while the drift current I_S is due to the diffusion of electrons from *n* to *p*.

Holes that diffuse to the *n*-region quickly recombine with some of the free electrons and disappear. This results in disappearance of some of the free electrons from *n*-region, and that small region will no longer be neutralized and a positive charge will exist in that region, now called the space-charge region. This happens on both sides of the junction.

The charge differential across the depletion region will create a potential difference or voltage with the n-region being the positive voltage with respect to the p-region's negative voltage. This difference will create an electric field that will oppose further movement of electrons and holes, decreasing I_D and I_S.

The drift current is a function of temperature and independent of the potential difference. Therefore, a junction that changes temperature would also change

its drift current and the width of its depletion region without necessarily affecting the diffusion current. In an open circuit condition however, the diffusion current would change to balance the drift current and return the system to equilibrium. The barrier voltage then remains constant.

If conducting terminals are installed on the exterior of the composite material, the voltage between the two terminals of a *pn*-junction measured would be zero and the depletion region voltage would not exist at the terminals due to metal-semiconductor contact voltage, otherwise we will have an energy cell, though charge is stored in the depletion region.

When the p-n junction is forward biased diffusion current is increased while drift current remains constant. The potential in the depletion region is also reduced hence reducing barrier voltage. This process continues until equilibrium is reached. A new capacitive effect, called the diffusion capacitance, will be seen.

In the reverse bias state, diffusion resistance and diffusion capacitance will go to zero while the depletion capacitance will increase. Electrons will flow from the n-material to the p-material while holes will flow in the opposite direction. The depletion region will in turn grow as more electron and holes are uncovered. Drift current will remain the same, as it is independent of the difference in potential. The change in potential across the junction will show up as an increase in voltage across the terminals with a negative voltage being registered at the p-end and a positive voltage being registered at the n-side. This will continue until equilibrium is reached.

C. SOLAR CELLS

A solar cell uses a p-n junction operating in reverse bias condition to break up electron-hole pairs by exciting the electrons. This is caused by photons of high enough energy levels entering the solar cell, exciting electrons to break their bonds and begin the migration to the collector terminals. If the electron does not recombine with another hole and form an electron hole pair then a potential difference is set up across the terminals. The load, in Figure 44merely takes advantage of the electron-hole pairs drive to recombine and reach an equilibrium state.

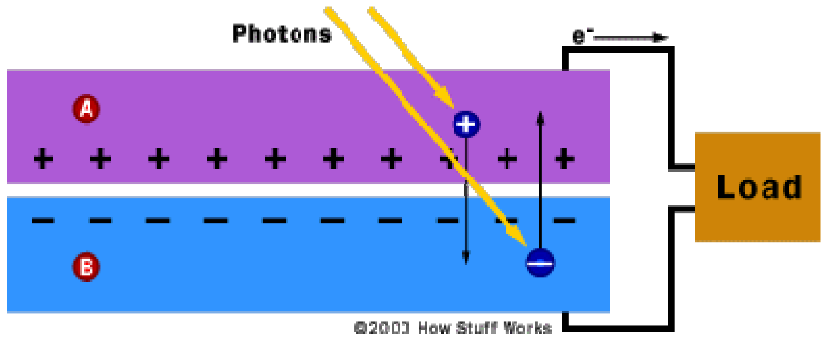

Figure 44 A p-type on n-type Solar Cell

For the purposes of power beaming, the receiver for laser-beamed power is a solar array, and so no new receiver technology is needed. Future arrays may be optimized for a fixed laser wavelength that would allow photovoltaic cells to achieve efficiencies of over 50%.[55] Typical efficiencies of solar cells operating on orbit are about 15%.

For cells near the optimum bandgap for solar conversion, such as GaAs with a band gap of 1.43 eV, the monochromatic light efficiency can be roughly estimated as double the conversion efficiency for sunlight. The best GaAs solar cells are slightly under 24% efficient for the solar spectrum, and thus can be expected to be about 48% efficient at the optimum wavelength.

The best photovoltaic cells can be expected to convert about 48% of monochromatic incident light at the optimum wavelength into electricity. The efficiency drops to zero for wavelengths much longer than the optimum.

In reality, solar cells do not perform optimally for photon energy out to the bandgap. Since light near the bandgap is only weakly absorbed most of its energy is converted to heat when striking the back plate of the solar cell or is reflected back out into space. Of all the photo energy received only about 30% can be converted.

Five percent of the energy received is lost to reflection when the silicon surface optimized for collection by application of a silicon-oxide anti-reflection coating. Without such a coating, reflection losses could reach as high as 36%.

55 G.A. Landis, "Photovoltaic Receivers for Laser Beamed Power in Space," *NASA Contractor Report 189075*, presented at 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, NV 7-11 Oct. 1991.

With only 45% of incident photons actually being utilized in silicon, some of the electrons recombine before reaching the collection grid. This is another contributing factor to decreased efficiency. The silicon thickness is the single most influential figure in recombination.

Some of the energy is lost in ohmic resistance between the semiconductor and the conducting base plate interface. More is lost in grid to resistance. To decrease these losses, a balance between larger grids has to be balanced by shadowing effects caused by the grid covering the semiconductor. Shadowing is optimized to eight percent for silicon. Line loss is another resistive loss lowering cell efficiency. By increasing line thickness resistance is decreased, but cost and weight is added to the solar array.

To protect the thin silicon cell from the cosmic environment a layer of glass has to be applied to the surface of the cell. The glass requires an application to adhere to the silicon surface. This application also has an absorption value that is minimizing but still contributory to inefficiencies.

Lastly, the substrate itself may have material defects and inconsistencies that will limit the efficiency through early recombination, and higher bad gaps.

As an example, silicon, with a bandgap of 1.24 eV, has a peak spectral efficiency of around 1.07 eV. As the wavelength gets longer, efficiency quickly drops off to zero. For the FEL with wavelengths about 1060 nm, the efficiency is off by a factor of three. Choosing a tailored coherent wavelength of 1100nm used in a SSL which is in the near-infrared efficiencies approaching 50% can be obtained. Also for wavelengths below 1100 nm, the response is linear giving a predictable loss. While it is possible to design solar cells that are optimized for below 1.07 eV the linear response drops quickly.

In the last ten years, solar cell manufacturers have made great strides in improving cell efficiency and power production. Multi-junction cells with greater than 28% efficiency are now commercially available. In a multi-junction cell, layers of different materials and doping levels are used to extract energy from different portions of the light spectrum, converting more of the photons into electrical power. Figure 45is a diagram of a Boeing Spectrolab Improved Triple-Junction (ITJ) cell showing the multiple layers grown on the Germanium wafer.

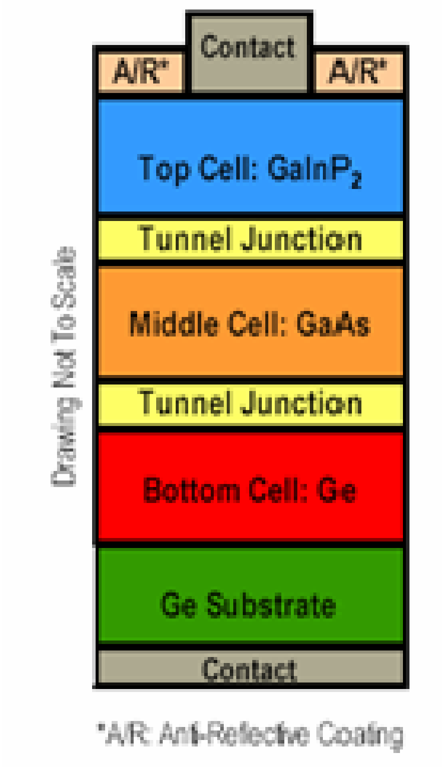

Figure 45 Multi-Junction Solar Cell

D. SUMMARY

Silicon, while still the most prevalent semiconductor for solar cells, is being eclipsed by Gallinium Arsenide (GaAs) which has a larger bandgap resulting in a higher per cell voltage and an increased energy transfer efficiency. Other more expensive and more exotic cells being developed offer greater efficiencies, but all work on the same principles illustrated here with silicon. The basics are the same.

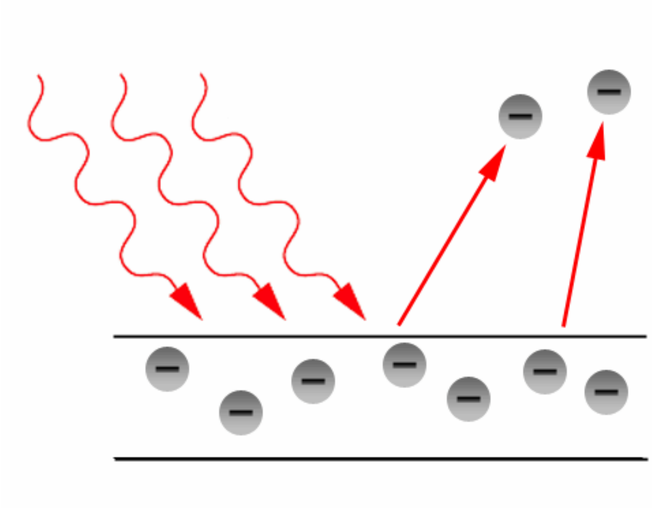

Figure 46 The Photoelectric Effect

Figure 46 depicts incoming photon wave radiation entering on the left and ejecting electrons, depicted as flying off to the right, from a substance.[56]

The use of better semiconductor technology such as changing the material combination used, adjusting dopant concentrations, and applying multi junction cell by layering different substrates to get a more efficient use of the spectrum have lead to greater power generation.

Now that we have discussed power beaming, lasers, optics, telescopes and finally solar cells, we have the information to put the entire process together. In the next chapter, we take a brief look at a future experiment that may use this information to take the first steps to making power beaming the mode of providing partial power to satellites in the near future.

56 Failex, " The Free Dictionary: Photoelectric Effect," <http://encyclopedia.thefreedictionary.com/_/viewer.aspx?path=7/77/&name=Photoelectric_effect.png>, (April 2006).

VII. NPSAT 1

A. CHAPTER OVERVIEW

This chapter looks at the possibility of conducting a power beaming experiment using a Naval Postgraduate School Satellite that is due to be launched this year. While completely powering a satellite from the ground for purposes of experimentation is currently impractical due to cost of the hardware and facilities, the technology is available to demonstrate that power beaming can work by transmitting and detecting a power beam on the surface of a satellite in orbit by measuring the I-V Curve increases using the Solar-Cell Measurement System (SMS) aboard the Naval Postgraduate School Spacecraft Architecture and Technology Demonstration Satellite 1 (NPSAT1).

B. NPSAT1

The Naval Postgraduate School will be placing its second satellite in orbit in October of 2006. The first satellite, the Petite Amateur Navy Satellite (PANSAT), was sent to orbit as a Get Away Special (GAS) package aboard the Space Shuttle. The satellite flew for a period of around 2.5 years before battery failure ended the mission. The satellite was in a low, roughly 240 km orbit.

The NPSAT1 is largely a Commercial Off-The-Shelf (COTS) constructed satellite. The goal of the NPSAT1 small satellite is to demonstrate a COTS-based Command and Data Handling (C&DH) subsystem using PC/104-compliant computer hardware along with a POSIX-compliant operating system, Linux.

The NPSAT1 will include a system to measure the performance of new experimental triple-junction solar cells. The measuring circuit in the SMS is based on a circuit developed at the Naval Postgraduate School many years ago. It will trace the cells' current-voltage (*I-V*) curves while in orbit. The System consists of a radiation-hardened microcontroller that uses a radiation-hardened FPGA to monitor a collection of sensors. A current-sink circuit is used to measure the current and voltage on the test cells. 24 cells on the satellite will be tested, 22 of which are the experimental cells, and two are dual-junction cells serving as reference cells.

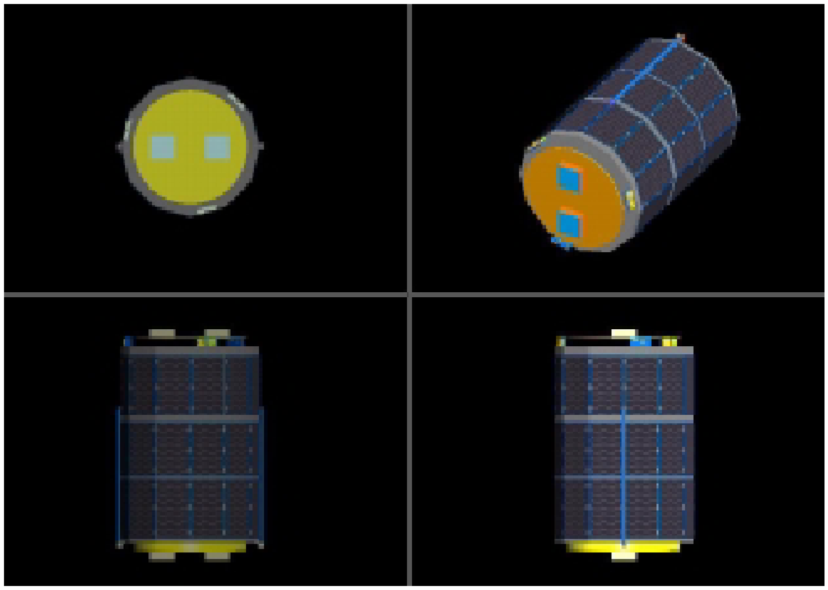

Figure 47 Graphic of the NPSAT1

The satellite itself is a 12-sided cylinder with body-mounted solar cells on all of the cylinder sides. Both ends of the cylinder have antennas mounted on them to allow for communications in the event the attitude of the spacecraft is not correctly nadir-pointing, see Figure 47.

The spacecraft subsystems include the C&DH, the electrical power subsystem (EPS), the attitude control subsystem (ACS), the radio frequency subsystem (RFS), and mechanical subsystems, which include spacecraft structure, mechanisms, and thermal design.[57]

The SMS is not an autonomous system and must work other subsystems of the satellite for power and communication with the ground station. The SMS is designed to measure the solar cells' performance.

The NPSAT1 will be launched into orbit aboard a MLV-05 Delta IV mission and placed at 560 km altitude with a 35.4% angle of inclination.

[57] D. Sakoda and J.A. Horning, "Overview of the NPS Spacecraft Architecture and Technology Demonstartin Satellite, NPSAT1, Pub for the 16th Annual AIAA/USU Conference on Small Satellites, (2005).

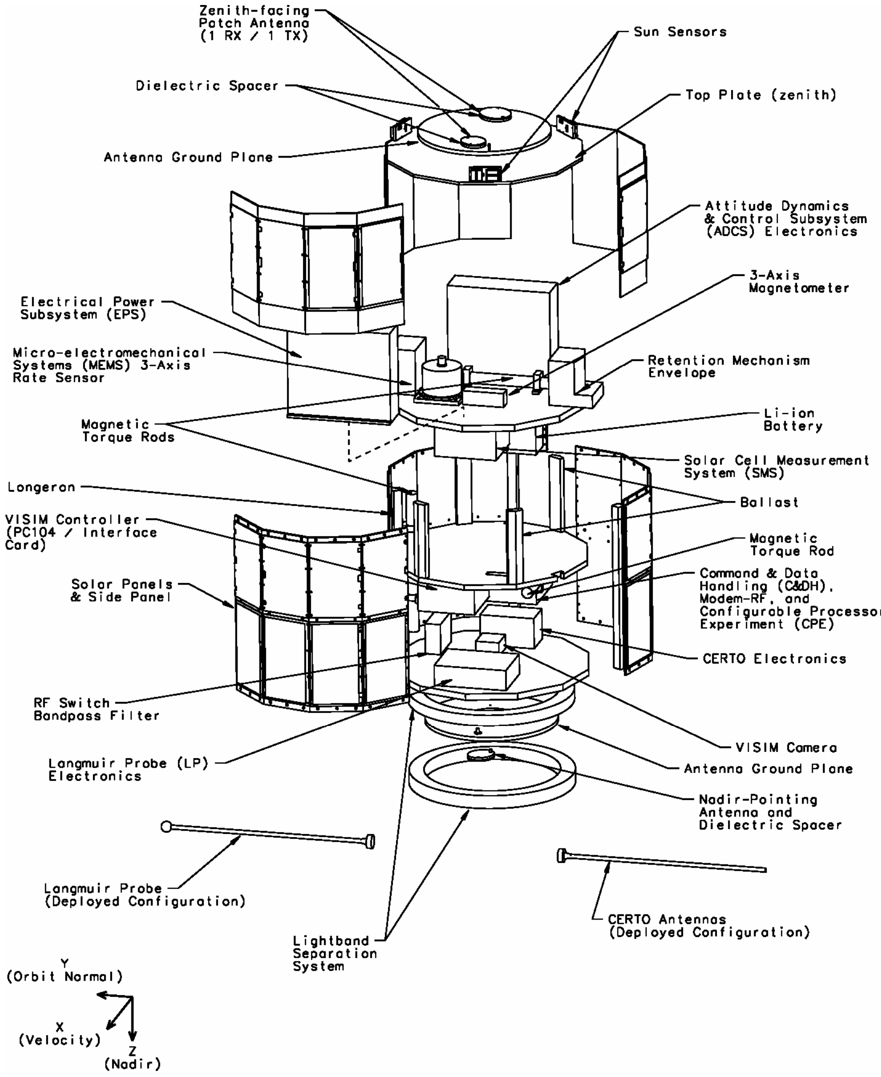

Figure 48 Exploded view of the NPSAT1

The main objective of NPSAT1 is to enhance the education of officer students at the Naval Postgraduate School. The launch of the NPSAT1 is ideal for a proposed experiment to measure power beamed from a ground-based telescope like the AMOS complex's 3.5-meter telescope in Maui. The SMS has down link telemetry capable of providing data on the transmission power and efficiency from orbit. Figure 48 shows an exploded view of the 180 pound satellite.

C. THE EXPERIMENT

With its primary mission of measuring solar cell conditions, NPSAT1 will be the prime candidate satellite to test the an experimental model that can determine the amount of energy received from a terrestrial based power beam. By using the facilities at AMOS in Maui, Hawaii, a low power laser beam of about 30 watts could be projected into space at the NPSAT1. Utilizing the SMS system, the change in energy generated can be directly related to the amount of energy transmitted to determine power beaming efficiencies.

The facilities at AMOS provide the necessary ground-based means to project a coherent beam of low power energy from the ground to the NPSAT 1 when it is launched in the fall of this year. This facility is uniquely available to NPS with the capability of a rapid pan telescope capable of tracking a LEO target.

A second benefit of this proposed power projection experiment is that it can also be used to verify tracking capabilities of the facilities at AMOS. With the NPSAT1 at LEO, moving at a velocity of about one revolution around the earth every 90 minutes, once the energy is detected and measured, a baseline can be established. Continued experimentation can be used to determine just how well the telescope is tracking the satellite in its orbit by measuring the change in I-V curve characteristics from the now established energy fluxuations.

There will be no need to make any changes to the proposed satellite for the purposes of this experimental concept. Since the NPSAT1 is already configured to measure the power generated by the triple junction solar cells, the addition of energy from the ground at any angle of incidence could simply be figured by subtracting the nominal power from the measured power to determine the effects over the entire I-V curve.

A third part of the experiment should look at the efficiencies associated with the used of monochromatic power beaming. First should be a look at how much voltage and current is transferred as seen by the I-V curve. Second should be a comparison to the theoretical increase in the voltage. This is in addition to the basic efficiency of power

propagation. Utilizing estimations of how much affective area of the power beam is available to affect energy transfer to the solar cell, calculations can be made as to the power transfer efficiency.

The distance to the satellite will be a critical component of the link budget solution. For a satellite like NPSAT 1, the distance can be calculated in accordance with Equation (7.1). Using the law of cosines:

$$\text{Slant range } (d_{ground,sat}) = (r_e + \text{alt})^2 + r_e{}^2 - 2(r_e + \text{alt})(r_e)\cos(\text{latitiude}) \qquad (7.1)$$

Since the AMOS facility is located at N 20°42’27.35293”, W 156°15’21.7” the distance to NPSAT 1 will be from directly overhead at 560 km to 2921.3 km at the horizon. With NPSAT 1 at an inclination angle of 35.4°, the maximum overhead time would be 12 minutes and 26.4 seconds when the orbit passes directly overhead. The NPSAT 1 becomes unmasked by the earth at S 4°11’20.4” latitude and never goes to a higher than 35.4°.

When discussing lasers used to beam power to a photovoltaic cell mounted to a spacecraft, if the spot size is smaller than the receiving array, the laser wavelength is chosen at the optimum value for the solar cell performance. However, if the diffraction-limited spot size is larger than the receiving array, it is desirable to decrease the wavelength to put more of the power on the array, even at the price of decreasing the efficiency. Since efficiency only decreases proportionately to the wavelength, while the illuminated area is proportional to the spot radius squared when atmospheric beam spreading is eliminated, it is desirable to use the shortest practical wavelength. The opacity of the atmosphere to short-wavelength ultraviolet places a lower limit to the wavelength at about 350 nm.[58]

Since a 3.5-meter spot beam is already larger than the proposed satellite, calculation of energy transmitted and received will need to take into consideration the effective beam area. Diffusion characteristics can be calculated as given in previous examples, though the square-law spreading is minimal at the distances discussed.

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[58] Geoffrey Landis, “Satellite Eclipse Power by Laser Illumination,” 8 July 2002, <http://powerweb.grc.nasa.gov/pvsee/publications/lasers/IAF90_053.html>, (April 2006).

D. SUMMARY

NPSAT1 offers a novel opportunity to test the long proposed theory of power beaming for spacecraft power supplementation. The innovative design of the NPSAT1 and pre-existing architecture of AMOS would lend itself completely to this proposed experiment without issue to other experiments that might be running at the time. Further, conducting the experiment from the existing facilities at the AMOS observatory in Maui, Hawaii, will provide the potential experimenters with a unique opportunity given that the satellite will be out of range of the primary ground support facility allowing for the dedicated measurements with no opportunity to affect any other investigations.

Proving the concept of power beaming will have wide-ranging ramifications. The Air Force, which had previously expressed interest in the project, will have the evidence it needs to go ahead with seeking funding for additional experimentation and future development. In addition, a successful experiment may very well be the launch pad for experiments using higher powers and larger satellites ultimately leading to a prototype system capable of providing power to GEO satellites.

VIII. SUMMARY AND FUTURE WORK

A. CHAPTER OVERVIEW

This chapter provides an overall summary of the power beaming argument to include a series of conclusions and suggestions for future research.

B. SUMMARY

Author Geoffrey Landis gave the following description of a system which could provide the capabilities discussed in this argument.

> Consider a baseline system with a wavelength λ near one micron, or 1000 nm ($1 \cdot 10^{-6}$ m). This is the wavelength range for an Nd: YAG laser, and close to that of a GaAs laser diode array. It is slightly longer than the optimum conversion wavelength for a Si solar cell. The distance surface-GEO) is $3.5 \cdot 10^{7}$ m, and the lens diameter is 2 meters. For diffraction limited beam spread, the diffraction-limited spot radius at GEO is 23 meters. This is sufficiently small that the beam spread at the array is almost entirely due to atmospheric turbulence. The turbulence-limited spot size is about 15,000 m^2.
>
> For 10 kW of baseline power with a solar array efficiency of 18.5%, the array area is 40 m^2, and so the array intercepts only about 0.25% of the beamed power. The required beam power would be 8.5 MW.
>
> It is reasonable to expect that use of adaptive optics could reduce the atmospheric beam spread by a factor of ten. The spot size is now limited by diffraction. If the laser wavelength is then reduced by a factor of two, to 500 nm, the total spot radius at GEO is 13 m. The illuminated area is 560 m^2, and the array now intercepts 7% of the incident power. The net result is that the laser power needed is about 500 kW.
>
> The required 500 kW could be provided, for example, by twenty-five 20-kw laser units, to allow any single unit to be taken off line without system failure. Such power levels are high compared to those achieved by current technology CW visible light lasers, but in the range likely to be reasonably achievable for future high-power lasers. It is many orders of magnitude higher power than currently achieved by diode lasers. Problems of tracking and reliability remain to be addressed.[59]

[59] Geoffrey Landis, "Satellite Eclipse Power by Laser Illumination," 8 July 2002, <http://powerweb.grc.nasa.gov/pvsee/publications/lasers/IAF90_053.html>, (April 2006).

With modern multifunction cells capable of providing efficiencies up to 28%, unforeseen in the 1990's, broadcast power requirements have come down. Laser capabilities have also come up to the point today that a 10kW class solid-state laser is a reality. Atmospheric disturbance can now be entirely compensated for by adaptive optics. Larger main mirrors in the new telescopes can further reduce the footprint of the beam on the satellite. All of these factors will further reduce the power generation requirement. The one factor that has changed to make the job more challenging is the rise of spacecraft bus power from 10 kW to 25 kW. Even this is not a problem with SSLs being produced in ever-increasing powers.

C. CONCLUSIONS

Technologies has reached the point today, should the parties responsible for spacecraft generation and launch get together and pool their resources, they could easily fund a development which would lead to a significant reduction in the cost of building and fielding new satellites by creating a network of ground based power beaming facilities. At just a few cents on the dollar, space missions could be extended. Also once the power beaming technology is in place and proven, future satellites could be redesigned to save weight and increase power as new more powerful SSLs become available. Political will based on lack of education in the area of directed energy and power beaming is really the only thing that is holding this landmark adventure from going forward.

D. FUTURE WORK

There are several areas for future improvements on this argument. First, who ever should take up this argument will need to explore the factions that need this information most, to stir more interest in its development. Very little information on specifically power beaming exists. Most of the information comes from the NASA Glenn Research Center. Recent budgetary constrains in the organization brought on by a resurgence in interest in manned space flight has led to these cuts.

The best follow-up to this work would to continue formulation of the NPSAT1 power beaming experiment proposed in Chapter 0. The use of the facilities at AMOS, as

they are military and have been available to NPS research in the past will make the most sense for this lower power experiment. The NPSAT1 is uniquely configured with architecture in place already to support the generation of I-V curves that will show exactly how much energy is being delivered and converted at the satellite on orbit.

Another area of follow-on research would be to look at main mirror efficiencies when different power beams are applied to derive some sort of theoretical base line. This study could be used in future calculations of efficiencies that would be available for proposed power beaming systems at higher powers.

Another area of interest is in supplying excess power to raise a satellites orbit. While briefly discussed in this argument as a reasonable use for power beaming, a much more detailed look should be focused on just this problem. The investigation should calculate the decrease in payload weight by reducing the need for a bi-propellant engine while maximizing the I_{sp} achievable to the space vehicle for orbit raising. It should take into account the reduction in vehicle launch weight and the possibility of using such a system in conjunction with power beaming to create a possible space tug capable of independently retrieving space debris, correcting billion dollar packages that are not in their orbits, and acting as a tug to bring high orbiting satellite down to LEO to receive maintenance and upgrade further extending their lives.

A future researcher might look more into power supply requirements. In particular, an investigation should look at exactly what efficiencies are presently capable in power generation, broadcast, link budgets, and solar cell conversion. Groundwork in this article was laid, but more in depth research is warrant.

An interesting follow-on would be a look more into telescope facility design for the purpose of power beaming. This would include speculation into the best possible locations to place these ground-based power-generating stations. A look at where the power will be supplied from or how it will be supplied might be incorporated. As larger mirrors are being developed for ground-based telescopes, some research should be focused on figuring out what is the best size for a projection aperture.

In line with all of the above should be a cost estimate of an entire system. One of my initial intensions was to find exact costs associated with development of ground based

systems, with spacecraft systems and with spacecraft development, but all sources sited in this area used broad generalities and cost estimates that varied by as much as 50%.

Since one large area that was introduced in the section on power beaming, namely solar cell annealing, could be of the utmost importance to long term satellite health, some focus should be conducted to augment the work already conducted by Professor Michael on solar cell annealing.

APPENDIX A: GLOSSARY

- **Attitude** - Position of a craft in space; determined by the inclination of its axis to a fixed reference point on the Earth.
- **Apogee** - Point in an Earth orbit where an orbiting body is farthest from the earth.
- **Argument of perigee** - The polar angle that locates the perigee (point where the satellite is CLOSEST to the earth) point of a satellite in the orbital plane; drawn between the ascending node, geocenter, and perigee; and measured from the ascending node in the direction of satellite motion.
- **Ascending node** - The point on the ground track of the satellite orbit where the sub-satellite point (SSP) crosses the equator from the Southern Hemisphere into the Northern Hemisphere. Traveling from South America up (ascending) to North America.
- **Altazimuth**: An **Altazimuth** or **alt-azimuth mount** is a simple mount used for moving a telescope or camera along two perpendicular axes of motion. The vertical movement is known as the altitude, while the horizontal motion is called the *azimuth*.[60]

The biggest advantage of alt-azimuth mounts is their simplicity in both manufacture and use. They are often used for beginner telescopes, or for spotting scopes, but are still widely in use for more advanced telescopes. In the latter case, advanced electronics and motors are sometimes attached to compensate for the restrictions of the mount's simplicity.

In astronomy, alt-azimuth mounts were, for a time, surpassed in popularity by the more complex equatorial mount. The latter is more naturally suited for tracking astronomical objects in the night sky as the Earth spins on its axis, since its polar alignment means that only one axis need be adjusted rather than the two of an alt-azimuth mount. Being able to track such objects reliably is particularly important for astrophotography, as well as more advanced amateur astronomy, both of which became more accessible when equatorial mounts became affordable.

60 Lefler, S.R., Wikipedia, “Altazimuth,” 3 April 2006, <http://en.wikipedia.org/wiki/Altazimuth>, (April 2006).

- **Beacon** - Most satellites have a fixed Morse beacon at the lower end of the satellites band-pass transponder. This is useful to detect when the satellite has crossed the horizon and is in range for operation. It can also be used to determine Doppler shifts.
- **BBS** - An electronic Bulletin Board System which users can use to leave and retrieve messages.

Figure 49 Birefringent Material: A calcite crystal laid upon a paper with some letters showing the double refraction

- **Birefringence**, or double refraction, is the division of a ray of light into two rays (the ordinary ray and the extraordinary ray) when it passes through certain types of material, such as calcite crystals, depending on the polarization of the light. This is explained by assigning two different refractive indices to the material for different polarizations. The birefringence is quantified by:[61]

$$\Delta n = n_e - n_o$$

where n_o is the refractive index for the ordinary ray and n_e is the refractive index for the extraordinary ray, Figure 49

Only the refraction of the ordinary or o-ray will follow Snell's law; in general the extraordinary or e-ray will not be co-planar with the incident ray or the o-ray, except for some special orientations.

> More generally, an anisotropic dielectric material has a dielectric constant that is a rank-2 tensor (3 by 3 matrix). A birefringent material corresponds to the special

61 http://en.wikipedia.org/wiki/Birefringence, last modified 22:22, 10 March 2006

cases of a real-symmetric dielectric tensor ε with eigenvalues of n_o^2, n_o^2, and n_e^2 along the three orthogonal principal axes of polarization. (Or, sometimes, only two axes are considered, corresponding to a single propagation direction.)

Cellophane paper is a cheap birefringent material.

Birefringent materials are used in many devices which manipulate the polarization of light, such as wave plates, polarizing prisms, and Lyot filters.

- **Cosmic Speed** - Five miles per second, the velocity required to put a satellite in Earth orbit; called first cosmic speed.
- **Drag** - Air resistance to a body in flight.
- **Descending node** - The point on the ground track of the satellite orbit where the sub-satellite point (SSP) crosses the equator from the Northern Hemisphere into the Southern hemisphere. Traveling from Canada down (descending) towards South America.
- **Doppler effect** - Apparent frequency change of waves which results when the source and recipient of the waves move toward, and then away, from each other. A shift in frequency caused by satellite movement toward or away from your location. When the satellite is coming toward you, the Doppler shift decreases the frequency. When the satellite is going away from you, the frequency increases. Like the waves from the ocean piling up in front of a storm.
- **Downlink** - The frequency which the satellite transmits to the Earth for reception by stations on Earth.
- **Eccentricity** - The orbital parameter used to describe the geometric shape of an elliptical orbit; eccentricity values vary from e = 0 to e = 1; where e = 0 describes a perfect circle and e = 1 describes a straight line. The amount a spacecraft deviates from a circular orbit.
- **Ephemeris** - Table indicating the computed positions of celestial bodies from day to day or at regular intervals throughout the year.
- **Elliptical Orbit** - Those orbits in which the satellite path forms an ellipse with the Earth at one focus.

- **Epoch** - The reference time at which a particular set of parameters describing satellite motion (Keplerian elements) are defined. The particular time the elements were produced.
- **Equatorial orbit** - Earth orbit with a plane near or identical to that of the equator.
- **Far Field**: The far-field region is the region outside the near-field region, where the angular field distribution is essentially independent of distance from the source. If the source has a maximum overall dimension D that is large compared to the wavelength, the far-field region is commonly taken to exist at distances greater than $2D^2/\lambda$ from the source, λ being the wavelength.[62]

For a beam focused at infinity, the far-field region is sometimes referred to as the Fraunhofer Region. Other synonyms are far field, far zone, and radiation field.

- **Fractiles**: Another numerical descriptor for the span of frequency distributions is the fractile. A p-fractile is defined as the x-value of the distribution which includes p*N observations, with 0<p<1 and N being the number of observations. An example may clarify this: the 0.1-fractile of the distribution shown in Figure 50 is 14.6, as it includes 10 % of all observations (starting from the left).[63]

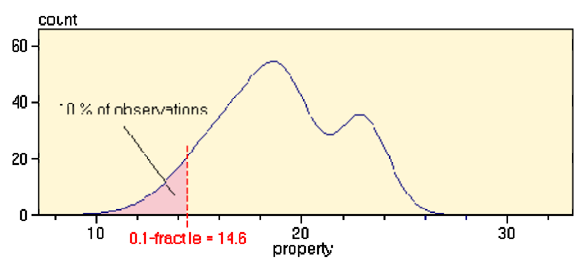

Figure 50 Shaded Area is a Depiction of a Fractile

- **Fraunhofer Region**: The region where the angular field distribution is essentially independent of distance from the source. If the source has a maximum overall dimension *D* that is large compared to the wavelength, the far-field region is commonly taken to

62 ATIS Committee, "Far-Field Region," 28 February 2001, <http://www.atis.org/tg2k/_far-field_region.html>, (April 2006).

63 Lohninger, H., "Fractiles," 16 July 2005, <http://www.vias.org/tmdatanaleng/cc_fractile.html>, (23 March 2006).

exist at distances greater than $2D^2/\lambda$ from the source, (λ) being the wavelength. For a beam focused at infinity, the far-field region is sometimes referred to as the Fraunhofer region. Synonyms far field, far zone, Fraunhofer region, radiation field.[64]

- **Full Width at Half Maximum**: A full width at half maximum (FWHM) is an expression of the extent of a function, given by the difference between the two extreme values of the independent variable at which the dependent variable is equal to half of its maximum value, see Figure 51[65]

FWHM is applied to such phenomena as the duration of pulse waveforms and the spectral width of sources used for optical communications and the resolution of spectrometers.

The term full duration at half maximum (FDHM) is preferred when the independent variable is time.

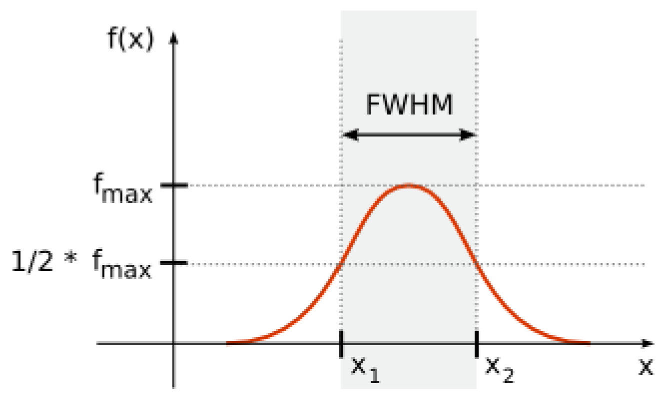

Figure 51 Full Width Half Maxim Graph

- **Geocenter** - The center of the Earth.
- **Geostationary orbit** - A satellite orbit at such an altitude (approx. 22,300 miles) over the equator that the satellite appears to be fixed above a given point. The satellite must also travel in the direction of the earth's rotation. The satellite remains in the same spot day after day, year after year.

64 ATIS Committee, "Fraunhofer Region," 28 February 2001, <http://www.atis.org/tg2k/_fraunhofer_region.html>, (23 March 2006)

65 Deville, Wikipedia, "Full-wave Half-maxim," 20 February 2006, <http://en.wikipedia.org/wiki/FWHM>, (23 March 2006)

- **Ground Station** - A radio station, on or near the surface of the earth, designed to transmit or receive to/from a spacecraft.
- **Ground track** - The imaginary line traced on the surface of the Earth by the subsatellite point (SSP).
- **Gyrotrons**[66] are high-powered electron tubes that emit a millimeter wave beam by bunching electrons with cyclotron motion in a strong magnetic field. Typical output powers range from 10s of kilowatts to 1-2 megawatts. Output frequencies range from about 20 to 250 GHz. Gyrotrons can be designed for pulsed or continuous operation. A prevalent application of gyrotrons is as a source of plasma heating in nuclear fusion research experiments.

- **Inclination** - The angle between the orbital plane of a satellite and the equatorial plane of the Earth.

- **Keplerian Elements** - The classical set of six orbital elements numbers used to define and compute satellite orbital motions. The set is comprised of inclination, Right Ascension of Ascending Node (RAAN), eccentricity, argument of perigee, mean anomaly and mean motion, all specified at a particular epoch or reference year, day, and time. A decay rate or drag factor is usually included to refine the computation.

- **Kepler, Johannes** - (1571-1630) German astronomer who determined the periods of revolution of the planets. Created "Kepler's laws" which read: 1) The path of every planet in its motion about the sun forms an ellipse, with the sun at one focus (see Elliptical orbit). 2) The speed of a planet in its orbit varies so that a line joining it with the sun sweeps over equal areas in equal times. 3) The squares of the planets' periods of revolution are proportional to the cubes of the planet's mean distances from the sun. Kepler was very active in astronomy throughout his whole life. He was once the astrologer and astronomer to Rudolph II of Bohemia. He also corresponded with Galileo and Tycho Brahe while at the university of Graz, Austria. In 1600, Kepler became Tycho's assistant in Prague. Kepler's laws removed all doubt that the earth and planets go

[66] Krash, Wikipedia, "EM Spectrum: Gyrotron," 11 December 2006, <http://en.wikipedia.org/wiki/Gyrotron,>, (23 March 2006).

around the sun. Later Newton used Kepler's laws to establish his law of universal gravitation. Kepler also invented the present-day form of the astronomical telescope.

- **Lyot filter:** named for its inventor Bernard Lyot, is a type of optical filter that uses birefringence to produce a narrow passband of transmitted wavelengths. Lyot filters are often used in astronomy, particularly for solar astronomy.

A Lyot filter is made from one or more birefringent plates (usually quartz), with (in multi-plate filters) each plate being half the thickness of the previous one. Because the plates are birefringent, light traveling through them is split into two rays (the ordinary and extraordinary rays), each experiencing a different refractive index and thus having a different phase velocity.

Only wavelengths at which the ordinary and extraordinary rays have optical path lengths equal to an integer multiple of the wavelength exit the plates in the same polarization state as they entered the plates. If the plates are surrounded by polarizers, this produces a filter with a transmission function with a comb of peaks. Rotating the plates shifts the wavelengths of the transmission peaks, allowing the filter to be tuned.

The separation and narrowness of the transmission peaks depends on the number, thicknesses, and orientation of the plates.

Single and multi-plate Lyot filters are often used inside the optical cavity of lasers to allow tuning of the laser. In this case, Brewster losses from the plate and other intracavity elements are usually sufficient to produce the polarizing effect and no additional polarizers are required.

- **Mean anomaly** - An angle that increases uniformly with time, starting at perigee, use to indicate where a satellite is located along its orbit. MA is usually specified at the reference epoch time where the Keplerian elements are defined. For AO-10 the orbital time is divided into 256 parts, rather than degrees of a circle, and MA (sometimes called Phase) is specified from 0 to 255. Perigee (closest to Earth) is therefore at MA = 0 and apogee (farthest away from Earth) is at MA = 127.

- **Mean motion** - The Keplerian element (a number) to indicate the complete number of orbits a satellite makes in one day. (i.e. 14.00374 orbits per day)

- **Microwaves**[67] are electromagnetic waves with wavelengths longer than those of infrared light, but shorter than those of radio waves.

Microwaves have wavelengths approximately in the range of 30 cm (frequency = 1 GHz) to 1 mm (300 GHz). However, the boundaries between far infrared light, microwaves, and ultra-high-frequency radio waves are fairly arbitrary and are used variously between different fields of study.

The microwave range includes ultra-high frequency (UHF) (0.3-3 GHz), super high frequency (SHF) (3-30 GHz), and extremely high frequency (EHF) (30-300 GHz) signals.

Above 300 GHz, the absorption of electromagnetic radiation by Earth's atmosphere is so great that it is effectively opaque, until the atmosphere becomes transparent again in the so-called infrared and optical window frequency ranges.

- **Nasmyth Focus:** A focal point to one side of the tube of a telescope with an altazimuth mount. It is formed by placing a third mirror (tertiary) to direct the beam along the altitude axis and through a hole in the supporting trunnions. Nasmyth foci enable bulky instruments to be mounted on a permanent platform that needs to rotate only in azimuth; they are commonly used with large modern telescopes, especially for spectrographic work. Named after the Scottish engineer James Nasmyth (1808-1890), best known for his invention of the steam hammer.[68]

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[67] Weir, D., Wikipedia, "EM Spectrum: Microwave," 28 January 2006, <http://en.wikipedia.org/wiki/Microwave>, (23 March 2006).

[68] David Darling, "Nasmyth Focus," <http://www.daviddarling.info/encyclopedia/N/Nasmyth_focus.html>, (23 March 2006).

- **Near-field region:** (also known as the *near field* or near zone) In the study of diffraction, the *near field* is that part of the radiated field that is within one quarter of a wavelength of the diffracting edge. Beyond the near field is the far field.[69]

The diffraction pattern in the near field typically differs significantly from that observed at infinity and varies with distance from the source

- **Seyfert Nuclei:** Seyfert galaxies were originally noted as having unusually bright, compact (star like) nuclei. The surroundings of this brilliant nucleus can take a variety of forms, perhaps carrying clues to how the central engine is fed or triggered. Some of these are shown in this selection of close-ups taken with the high-resolution Planetary Camera (PC) CCD on HST's Wide Field Planetary Camera 2. Some of these nuclei are surrounded by either tight rings or annuli of star formation (NGC 1019, NGC 7469), and others show intricate dust structures around the nucleus that are not apparent from ground-based images (NGC 3516). The spiral pattern around the nucleus of NGC 3393 comes from ionized gas, rather than stars, and is excited to shine upon absorption of the intense ultraviolet light from the nucleus. Markarian 1376 shows a cone of gas similarly illuminated by the nucleus; any counterpart on the other side is hidden by the prominent absorbing dust in the galaxy. The close-up of IC 4329A shows that we see its nucleus just through the edge of dust farther out in its disk. In many of these, the nuclei are strongly overexposed to show the surrounding galaxy, producing diagonal diffraction spikes and other image artifacts.[70]
- **Spatial frequency** is a characteristic of any structure that is periodic across position in space. The spatial frequency is a measure of how often the structure repeats per unit of distance. In optics, it is measured in lines per millimeter, 1000th of the SI unit.[71]

In wave mechanics, the spatial frequency ν is related to the wavelength λ by

69 Check, E.R., Wikipedia, "Far-Field," 16 January 2006, <http://en.wikipedia.org/wiki/Far-field>, (23 March 2006)

70 Keel, "Closeup views of Seyfert nuclei from HST," <http://www.astr.ua.edu/keel/agn/synuclei.html>, (23 March 2006).

71 Ian Cairns, Wikipedia, " Spatial Frequency," 8 February 2006, <http://en.wikipedia.org/wiki/Spatial_frequency>, (23 March 2006).

$$\nu = \frac{1}{\lambda}$$

Likewise, the wave number *k* is related to spatial frequency and wavelength by

$$k = 2\pi\nu = \frac{2\pi}{\lambda}$$

- **Temporal frequency** is a little more nebulous. It is measured in Hertz. It is the rate of change of light reaching a receptor. Temporal or time in this application is not constant and exhibits a cyclic nature that can be quantized. Temporal frequency would best be defined as a characteristic of any structure that would seen as periodic across a given length of time. In this instance, it is the front of a time wave that appears to brighten and darken with its cyclic change in frequency.

A fundamentally related but different method of describing the performance of an electronic circuit is by means of its temporal frequency response. A plot is made of the response for a series of input signals of a variety of frequencies. The response is measured as the ratio of the amplitude of the signal obtained out of the system to that put in. If there is no loss in the system, then the frequency response is unity (one) for that frequency; if a particular frequency fails to pass through the system, then the response is zero. Again, analogously the optical system may also be described by defining a spatial frequency response.[72]

- **Trunnion:** A cylindrical protrusion used for mounting.

72 Encyclopedia Britanica On-line, “Temporal frequency response,” <http://www.britannica.com/eb/article-37984>, (23 March 2006).

APPENDIX B: VLT ACTIVE OPTICS SYSTEM

The VLT active optics system is an example of an active optics system that is in use today on the Very Large Telescope (VLT) in Paranal, Chile. This telescope has an additional adaptive optics system that was discuss in the section on adaptive optics.

> Due to the low ratio between their thickness and their diameter, the VLT primary mirrors will be rather flexible and sensitive to various disturbances, requiring permanent control of their optical shape.[73]
>
> Active optics consists in applying controlled forces to the primary mirror and in moving the secondary mirror in order to cancel out the errors. The scheme was developed by ESO for the 3.5-m New Technology Telescope (NTT) and is now applied to the VLT. The system must essentially compensate for static or slowly varying deformations such as manufacturing errors, thermal effects, low frequency components of wind buffeting, telescope inclination, ... It is also used when changing between Cassegrain and Nasmyth foci.
>
> A schematic view of the system is shown in Figure 52

A. DESCRIPTION

The different elements of the active optics system of the VLT are the primary mirror, with its active support system located within the M1 Cell structure, the M2 unit, the CCD Shack-Hartmann wavefront sensor (WFS) located in the sensor arm of the adapter, and the computer analyzing the wavefront sensor data. There are three modes of operation, that are described below

B. BASELINE

The active optics baseline operation is the correction of wavefront aberrations generated by the optics of the telescope and by slowly varying temperature inhomogeneities in or near the building. The corrections are based on an image analysis.

The active optics system constantly monitors the optical quality of the image using an offset reference star as it is picked up in the field by the wavefront sensor CCD in the adapter sensor arm. The same offset star is also used by the acquisition and autoguiding CCD.

73 ESO, "The VLT Active Optics System," 22 June 1998, <http://www.hq.eso.org/projects/vlt/unit-tel/actopt.html>, (February 2006).

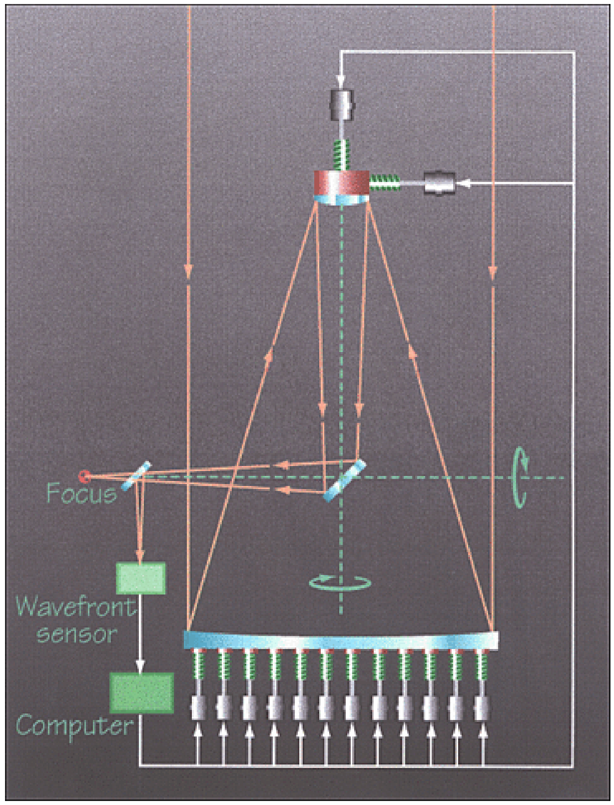

Figure 52 The VLT Active Optics System

The system controls the relative position and the shape of the optical elements. The primary mirror shape can be actively controlled by varying the force pattern applied by means of its support system. The latter consists of 150 computer controlled axial actuators, applying a distribution of forces at the back of the mirror.

Periodically the image analyzer calculates the deviation of the image from the best quality. The image analysis typically requires about 30 seconds (1/30 Hz) in order to integrate out the effect of atmospheric seeing. The computer decomposes the deviation into single optical contributions (defocus, astigmatism, coma etc...) and calculates the force correction which each active element has to perform to achieve the optimal quality. The set of 150 correction forces, one for each axial actuator, is computed and transmitted to the local control of the M1 Cell-M3 Tower for execution. The focus and coma terms are corrected by displacements of the secondary mirror.

C. FAST CORRECTIONS

The feedback scheme is the same as above but here the maximum frequency for fast corrections is 1 Hz. These shorter integration times reduce the signal to noise ratio of measurements and affect both the sky coverage (requirement of brighter

guide stars in the field) and the number of aberrations which can be corrected (only the lowest spatial frequency ones).

D. OPEN LOOP CORRECTIONS

This mode does not use feedback information from the image analyzer. The open loop mode is used in the absence of any sufficiently bright guide star, or in the case of image analysis failure, or as initialization for baseline operation after a new telescope preset. For this type of operation, accurately predicted forces on M1 (dependent on telescope tube inclination) and predicted positions (dependent on temperature) are required.

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APPENDIX C: IMAGE CORRECTION

The following is another except from the AdOpt reference. It is important to the understanding of the way the AdOpt module works and is included here in the interests of completeness.

> A pick-up mirror folds the light beam coming from M3 into the optical train of the AdOpt module where a first off-axis parabola reimages the pupil onto the Deformable Mirror In Figure 10. The off-axis parabola is also the T/T mirror compensating the centroid motion of the image due to the low spatial frequencies component of the atmospheric turbulence. The T/T device has four voice-coil actuators whose stroke is controlled through capacitance sensors used in a differential mode to drive the control loop and giving, in this way, a great accuracy in the mirror positioning measurements. There is also a dummy mass to counter-balance the angular momentum of the device. The bandpass of the T/T mirror is about 1.5KHz and, on the average, the actuation delay time is 1.35ms.
>
> The DM is the mirror for the HO compensation. It is a continuous face sheet mirror with 97 magnetostrictive actuators; it reflects the beam to a second off-axis parabola that forms the image on the detector focal plane.
>
> This optical train gives a global focal ratio of F/32.2 and does not affect the image quality of the telescope even for diffraction limited images over a field of view of 1×1 arcmin in the near IR (J, H, K) and of 30×30 arcsec in the visible (V, R). The light is sent directly to the NIR imager or, by inserting a flat folding mirror, to the optical imager (OIG): the number of total reflections after M3 are 4 in the IR and 5 in the visible. All the mirrors have a silver protected coating with a reflectivity of at least 95% in the visible and 98% in the IR.

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APPENDIX D: WAVEFRONT SENSING

The following information was moved to this appendix, as it is highly technical in nature and more pertinent to the researcher with a high degree of education in optics. It does contain collateral information on the tip/tilt system and is there for pertinent to the argument and worth including.

> The beam to the wavefront sensing area is collected after the second off-axis parabola through a four positions wheel with a set of dichroic filters. The spectral responsivity of the dichroics can be chosen between respectively Tx = 50% and Rx = 50% of the light in the range between 0.45 µm and 2.2 &micero;m, then Tx = 90% and Rx = 10% in the same spectral range and finally Tx = 100% for the IR light (approximately from 0.9 µm) and Rx = 100% for the visible spectrum to the WFS; the fourth position of the wheel is empty for the speckle camera and for using the AdOpt optical train as a simple focal extender for the two imagers.
>
> Two kinds of T/T sensors can be used.
>
> - The APD T/T sensor has an optical image dissector splitting at F/200 the light of the guide star into four beams towards four avalanche photo diodes (APD). Using the difference between the APDs' signals the centroid position of the star is retrieved and the correction through the T/T mirror is applied. The APDs have a maximum sensitivity at 0.7 µm with a quantum efficiency peak of 65% and a passband of 220nm.
> - The pyramidic wavefront sensor can be used both for the T/T only correction and for the HO correction. The guide star is focused on the vertex of a pyramid with 13 µm roughness on the edges and a 174º vertex angle. The pyramid (which can be vibrated up to 100Hz with 250 µm Peak to Valley amplitude) together with a reimaging optics produces four pupil images onto a four quadrants read-out 80×80pixels EEV39 CCD.
>
> A fast CCD controller allows for up to 400Hz frame rate with only seven electron RMS Read Out Noise. The wavefront computer is a real-time matrix multiplier able to evaluate slopes from pixels intensities and to multiply current and past measured slopes with a user provided matrix. Latency time of the wavefront computer is less than 260µs.
>
> A nutating mirror just before the wavefront sensing area allows for off-axis corrections and to maintain the guide star in the sensor field of view in case of targets with proper motion such as asteroids.

A. TIP-TILT PERFORMANCES

Only The Tip-Tilt correction is fully operating at the TNG Nasmyth A focus and serves the IR imager.

The Tip-Tilt system needs a guide star to sense the jitter induced by the atmosphere in order to apply an efficient correction. The sharper and the brighter is the guide star the better is the correction. It becomes mandatory to have in the neighborhoods of the astronomical target a source satisfying these requirements. The guide star could be the target itself (the best situation) or a star bright enough located within 30" from the center of the field: in these cases a correction getting worse with the angular distance is expected. We recommend to not exceed the limit of 30" and to consider only guide stars brighter in V or R than Mag=13.

The larger is the observational wavelength the better is the correction under the same seeing conditions. Good performances are expected for K and K' bands, discrete for H band, poor for J. At shorter wavelengths it is also foreseen a small improvement of resolution mainly due to telescope tracking errors compensation, if any.

The better is the seeing the better is the correction: depending on the observational wavelength, there is a limit over which any correction is useless. This limit is more relaxed in K and K' and it becomes severe as the wavelength decreases.

Some particular atmospheric conditions could change the correction performances of the Tip-Tilt system such as variations of the isokinetic angle that depends on the vertical distribution of the atmospheric turbulence.

The asymptotic values for dimmer magnitudes represent the natural FWHM due to the seeing at the corresponding wavelength. Even in K band the corrected FWHM never goes to the diffraction limit because a static blur of 0.1" due to the overall optical system (telescope+AdOpt+NICS) is introduced.

APPENDIX E: THE ADAPTIVE OPTICS PACKAGE

In an on going effort for completeness, but without the intent of reinventing the wheel, the following discussion is taken from AOA incorporated's description of the adaptive optics system.

> An adaptive optics system automatically corrects for light distortions in the medium of transmission. For example, if you look far down a road on a very hot and sunny day, you will often see what is usually called a mirage. What you are seeing is the rapidly changing temperature in the air causing it to act like a thick, constantly bending lens.[74]
>
> An adaptive optics system measures the characteristics of the lens and corrects for it by means of a deformable mirror controlled by a computer. The device that measures the distortions in the incoming wavefront of light is called a wavefront sensor.
>
> Light from a nominal point source above the atmosphere enters the primary aperture and is split between a camera and a wavefront sensor as in Figure 53 The sensor measures the wavefront distortion and controls a tilt mirror to stabilize the image and a deformable mirror that restores the image sharpness lost to atmospheric turbulence. The adaptive optics system technologies developed and delivered by AOA include adaptive wavefront compensation for optical systems and wavefront measurement. In recent years, the technology and practice of adaptive optics have become, if not commonplace, at least well-known in the astronomical community.

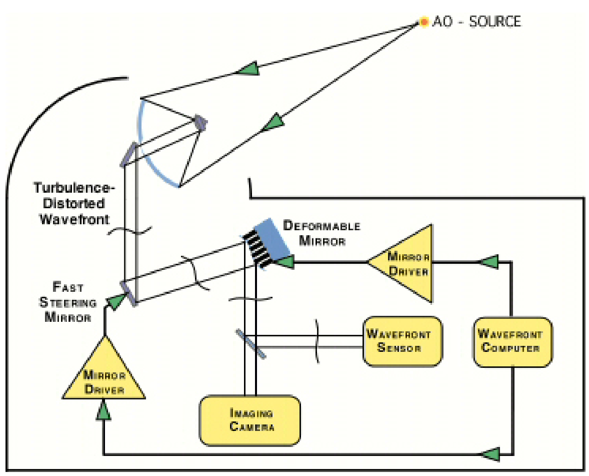

Figure 53 An Adaptive Optics System

[74] Adaptive Optics Associates, "Adaptive Optics Tutorial," <http://www.aoainc.com/technologies/adaptiveandmicrooptics/aostutorial.html>, (April 2006).

A key technology supplied by AOA is the wavefront sensor. The most commonly used approach is the Shack-Hartmann method, as shown in Figure 54This approach is completely geometric in nature and so has no dependence on the coherence of the sensed optical beam. The incoming wavefront is broken into an array of spatial samples, called sub-apertures of the primary aperture, by a two dimensional array of lenslets. The sub-aperture sampled by each lenslet is brought to a focus at a known distance F behind each array. The lateral position of the focal spot depends on the local tilt of the incoming wavefront; a measurement of

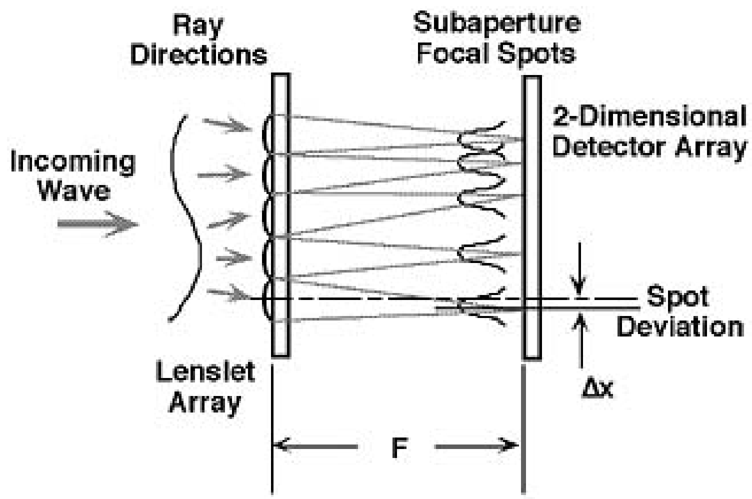

Figure 54 Shack-Hartmann method

all the sub-aperture spot positions is therefore a measure of the gradient of the incoming wavefront. A two-dimensional integration process called reconstruction can then be used to estimate the shape of the original wavefront, and from there derive the correction signals for the deformable mirror.

The incoming wavefront sample is analyzed into spatial sub-apertures by a miniature lens array which creates a pattern of spots on a two-dimensional array. The deviation of each spot from its nominal center is proportional to the input tilt at the corresponding sub-aperture.

The transformation from spot array to wavefront output is illustrated in Figure 55 The processing steps are shown clockwise from upper left, digitized spot pattern, vector representation of the spot deviations from nominal, reconstructed mirror profile, and Zernike decomposition. At center is the simple optical arrangement that makes the measurement possible.

To appreciate the daunting task faced by designers of adaptive optics systems, one should understand that an initially plane wavefront traveling 20 km through the turbulent atmosphere accumulates, across the diameter of a large telescope, phase errors of a few micrometers. These have to be sensed with a minimum number of photons and corrected to about 1/50 of a micrometer every millisecond or so.

Another complication is that, for short integration times, the field of view over which the atmospheric wavefront distortions and hence the images are correlated, the isoplanatic angle, is very small (only a few arc second for visible wavelengths).

Because of the high bandwidth and the small field to which correction can generally be applied, adaptive optics uses a small deformable mirror with a diameter of 8 to 20 cm located behind the focus of the telescope at or near an image of the pupil. In some current projects, the possibility of using a large deformable secondary mirror is being developed. The choice of the number of (usually piezoelectric) actuators is a tradeoff between degree of correction, use of faint reference sources (see below) and available budget. For instance, a near-perfect correction for an observation done in visible light (0.6 /265m) with an 8-m telescope would require ~ 6400 actuators, whereas a similar performance at 2 /265m needs only 250 actuators.

A large number of actuators require a similarly large number of subapertures in the wavefront sensor, which means that for correction in the visible, the reference star should be ~ 25 times brighter than to correct in the infrared. Most current astronomical systems are designed to provide diffraction-limited images in the near-infrared (1 to 2 /265m) with the capability for partial correction in the visible. However, some military systems for satellite observations in the USA do provide full correction in the visible on at least 1-m class telescopes.

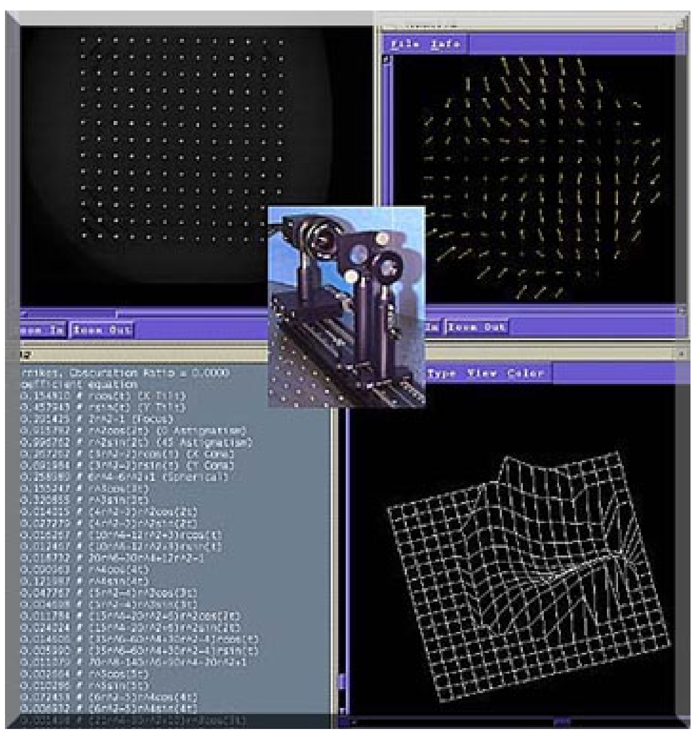

Figure 55 Transformation from spot array to wavefront output

Two main methods are used to measure the degraded wavefront, the Shack-Hartmann device, which measured the slope of the wavefront from the positions of the images of the reference star given by each subpupil, and curvature sensing, where the intensities measured in strongly defocused images provided directly give the local curvatures of the wavefront. Correction in the Shack-Hartmann device is made with individual piezoelectric actuators. Correction in a curvature sensing system is accomplished with a bimorph adaptive mirror, made of two bonded piezoelectric plates. With both methods, wavefront sensing is done on a reference star, or even on the observed object itself if it is bright enough and has sufficiently sharp light gradients. The measurement can be performed in the visible for observation in the infrared, or in the infrared itself (1 to 2 /265m), if e.g. the reference star is too faint in the visible.

The control system is generally a specialized computer that calculates from the wavefront-sensor measurements the commands sent to the actuators of the deformable mirror. The calculation must be done fast (within 0.5 to 1 ms), otherwise the state of the atmosphere may have changed rendering the wavefront correction inaccurate. The required computing power needed can exceed several hundred million operations for each set of commands sent to a 250-actuator deformable mirror. As in active optics systems, zonal or modal control methods are used. In zonal control, each zone or segment of the mirror is controlled independently by wavefront signals that are measured for the subaperture corresponding to that zone. In modal control, the wavefront is expressed as the linear combination of modes that best fit the atmospheric perturbations.

AO Operation is strongly affected by the size of the isoplanatic angle, usually ~ 20" at 2 /265m, but only ~ 5" at 0.6 /265m. It is generally NOT possible to find a sufficiently bright reference star close enough to an arbitrary astronomical object. Conditions are much better in the infrared than in the visible since atmospheric turbulence (and especially its high spatial frequencies) has, for a given AO correction, a weaker effect on longer wavelengths. The spatial and temporal sampling of the disturbed wavefront can therefore be reduced, which in turn permits the use of fainter reference stars. Coupled with the larger isoplanetic angle in the IR, this gives a much better outlook for AO correction than in the visible.

Nevertheless, even for observations at 2.2 μm, the sky coverage achievable by this technique (equal to the probability of finding a suitable reference star in the isoplanatic patch around the chosen target) is only of the order of 0.5 to 1%. It is therefore quite normal that most scientific applications of AO so far have been on objects which naturally provide their reference object like solar system small bodies, stellar environments, stellar clusters and a few very bright Seyfert nuclei.

APPENDIX F: ADVANCE ADAPTIVE OPTICS

A. LASER GUIDE STARS

The following excerpt talks about the use of reference stars for the purposes of fine tuning adaptive optics. Atmospheric affects are taken into account and the adaptive system compensates for the atmospheric distortion giving resolutions near the diffraction limit.

> The most promising way to overcome the isoplanatic angle limitation is the use of artificial reference stars, also referred to as laser guide stars (LGS) Figure 56These are patches of light created by the back scattering of pulsed laser light by sodium atoms in the high mesosphere or by molecules and particles located in the low stratosphere. The laser beam is focused at an altitude of about 90 km in the first case (Sodium resonance) and 10 to 20 km in the second case (Rayleigh diffusion). Such an artificial reference star can be created as close to the astronomical target as desired, and a wavefront sensor measuring the scattered laser light is used to correct the wavefront aberrations on the target object.[75]
>
> Several laboratories in the United States, operating under military contracts, have reported the successful operation of adaptive optics devices at visible wavelengths with a laser guide star on a 60-cm telescope [Defense Advanced Research Projects Agency (DARPA), Maui Optical Station (AMOS) situated on top of Mount Haleakala in Maui, Hawaii] and on a 1.5-m telescope (U.S. Air Force Starfire Optical Range). Both got images with ~ 0.15 arc sec resolution and proved the feasibility of laser probes. A joint program of the Strategic Defense Initiative Organization (SDIO) and the U.S. Navy reported an improved resolution by almost a factor of 10 on a 1-m telescope in San Diego, California. Some systems for astronomical.
>
> Nevertheless, there are still a number of physical limitations with an LGS. A first problem, focus anisoplanatism, also called the cone effect, became evident very early on. Because the artificial star is created at a relatively low altitude, back-scattered light collected by the telescope forms a conical beam, which does not cross exactly the same turbulence-layer areas as the light coming from the distant astronomical source. This leads to a phase estimation error, which in principle may be solved by the simultaneous use of several laser guide stars around the observed object. The effect is minimized with the sodium resonance technique and roughly equivalent on an 8-m telescope to the phase error experienced with an NGS 10" away from the astronomical target. This in particular leads to still reasonable performance at 2 /265m with a ~ magnitude 9 beacon.

[75] ESO, “An Introduction to Adaptive Optics,” 21 September 2000, <http://www.eso.org/projects/aot/introduction.html>, (March 2006).

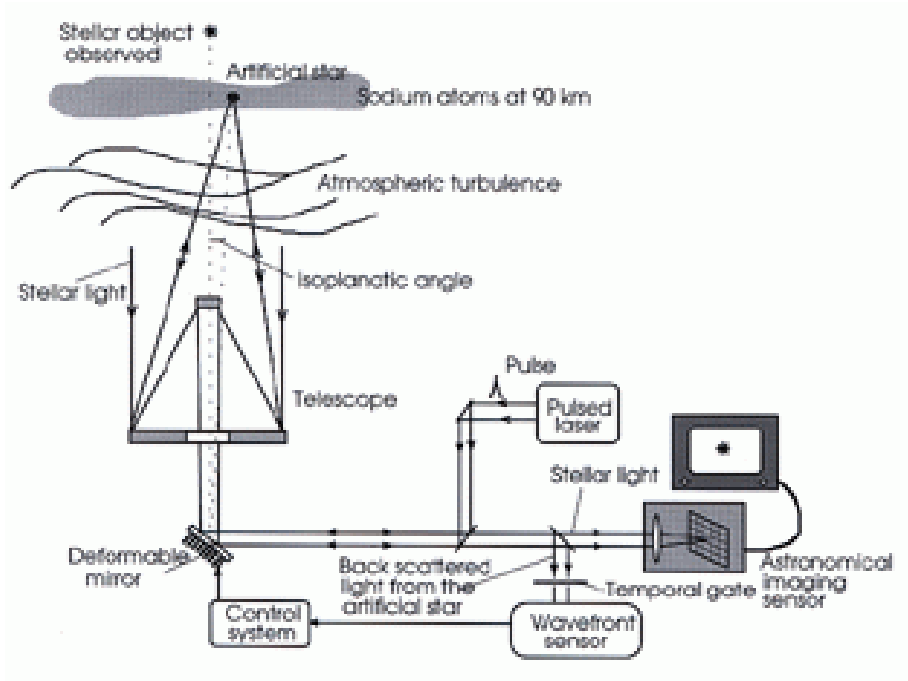

Figure 56 Adaptive Optics with Laser Guided Star

Even more severe is the image motion or tilt determination problem. Because the paths of the light rays are the same on the way up as on the way down, the centroid of the artificial light spot appears to be stationary in the sky, while the apparent position of an astronomical source suffers lateral motions (also known as tip/tilt). The simplest solution is to supplement the AO system using the LGS with a tip/tilt corrector set on a (generally) faint close NGS. Performance is then limited by the poor photon statistics for correcting the tip/tilt error. A more performant (and complex) solution would be to use two different AO systems with two laser beacons, one, for the astronomical object and one for the reference star. Tip/tilt photon statistics would then be much increased by the star sharpening provided by the 2nd AO system.

With the latter technique, fainter natural reference stars can be used to measure the image motion, so the probability of finding such a reference star close to the astronomical object is higher, This concept of dual adaptive optics therefore provides a better sky coverage (up to 80% for an 8-m telescope at 1- 2 µm). An obvious implication is that the larger the telescope, the greater the sky coverage because the gain in resolution brought about by the increase of the diameter of the optics is fully exploited. On the other hand, it has severe technological implications, as it requires the duplication of all components (deformable mirror, wavefront sensor, and laser guide star).

Adaptive optics with a multicolour laser probe is another concept investigated to solve the tilt determination problem of laser beacon based AO. Only applicable to sodium resonant scattering at 90 km, it excites different states of the sodium atoms and makes use of the slight variation in the refraction index of air with wavelength. Its main drawback is the limited returned flux, owing to the saturation of mesospheric sodium layer. The multicolour laser guide star may provide corrections without any natural reference star, resulting in a 100% sky coverage, but current tests are not totally encouraging.

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APPENDIX G: ADVANCED ADAPTIVE OPTICS II

A. MULTI-CONJUGATE ADAPTIVE OPTICS (MCAO)

The following excerpt talks about the use of reference stars for the purposes of fine tuning adaptive optics. Atmospheric affects are taken into account and the adaptive system compensates for the atmospheric distortion giving resolutions near the diffraction limit.

1. Adaptive Optics Uses

> The most evident use is direct imaging with filters. All AO systems provide this basic mode, often supplemented with a scanning filter (circular variable filter or scanning Fabry-Perot) to get full data cubes with both the 2D spatial and 1D spectral information on the astronomical targets. Getting these data cubes in a single exposure is very attractive, given the time variable nature of turbulence, even after AO correction. This can be done by the so-called Integral Field Spectrographs (IFS). Their use with AO corrections has been pioneered by OASIS at CFHT in the visible and 3D at Calar Alto for the near-IR. Similar instruments are being developed for the 8-ms, in particular GMOS in the visible at Gemini and SINFONI -SPIFFI in the near-IR at the VLT. GMOS also features a unique multi-slit capability coupled with Adaptive Optics.

The following conclusions were drawn about adaptive optics, are warrant to our discussion, and therefore included as a wrap-up on adaptive optics.

B. CONCLUSION

> There are many substantial technological challenges in AO. Among them are the development of fast, very low-noise detectors in order to be able to correct with fainter reference stars; high-power reliable & easy to operate sodium lasers; very fast processors exceeding 109 to 1010 operations per second; deformable mirrors with bandwidths of several kilohertz and with thousands of actuators, and large secondary adaptive mirrors. The latter are especially interesting at thermal wavelengths, where any additional mirror raises the already huge thermal background seen by the instruments.

> NGS-based AO in the Infrared is routinely achieving near diffraction-limited images and spectroscopic data cubes on large telescopes up to the present generation of 8-10 m diameter. Significant corrections have been obtained in the visible in exceptionally good seeing conditions, but diffraction-limited performance has up to now .... Single LGS systems are now or soon operating at a

number of Observatories, but routine demonstration of their potential for getting very high sky coverage has not yet been achieved. MCAO techniques are still in their infancy.

Many recent astronomical discoveries can be directly attributed to new optical observation capabilities. With the new generation of Very Large Telescopes entering into operation, the role of AO systems (and for even better resolution, interferometry) is extremely important. With this capability, their huge light-gathering along with the ability to resolve small details, both spatially and spectrally, has the potential to bring major advances in ground-based astronomy in the new decade. Further down the line, the giant optical telescopes under discussion, like OWL, will rely on advanced AO systems for basically ALL their observations; they will have to be incorporated right at the start of the projects.

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